AN APPLICATION OF THE ENGINEERING PRODUCTION FUNCTION TO TECHNOLOGICAL CHOICE: A DYNAMIC PROGRAMMING APPROACH TO DAIRY PROCESSING.

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I declare that this thesis has been composed by myself and that the work incorporated in it is my own.

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CONTENTS

CONTENTS PAGE

CONTENTS PAGE

CONTENTS PAGE

CONTENTS PAGE

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This thesis considers an alternative to the standard aggregate statistical price-based studies of production which are often used to inform policy in new enterprises. The study recognises the limited applicability of the results of these studies, in which the underlying production relations are masked by prices, and technology differences are hidden by the degree of aggregation. The study also recognises the inadequacies of the micro studies on Technology choice.

The thesis adopts an engineering approach so that the underlying relationships between inputs and outputs may be unmasked. Using this engineering approach, the production process is viewed as the application of energy to materials. The energy sources (men, electricity, fuel, etc.) are combined with instruments of energy application (machines, boilers etc.) to transform the material input into some desired output. By applying certain engineering principles (esp. in thermodynamics, hydraulics, etc.), the engineering variables (heat, speed, etc.) are converted to physical variables (steam, motor size, etc.), to which prices can be attached for an economic analysis of the alternative systems. The "appropriate" choice is considered coincident with the least-cost choice, and market or social prices may be attached to the physical variables to reflect relative factor scarcities in any particular economic environment.

The analysis of technology choice is done initially at the sub-process level (production stage) with the stages being based on the unit operations of food processing. The "appropriate" composite plant level technology is found using the technique of Dynamic Programming, which avoids a handicap of earlier technology studies, by taking stage interrelationships into account. The FORTRAN Coded programme used the physical factor quantities as its input and allows variation in the factor prices attained for greater flexability and wider applicability of the data generated by the study.

CHAPTER 1

INTRODUCTION

1.1 Perspective

In recent years some Economists have been becoming increasingly disenchanted with the standard aggregate statistical production and cost functions, which are often used to inform policy on the selection of new manufacturing enterprises. The limited applicability of the results of such studies are seen to stem not only from the level of aggregation which masks the vast differences that could exist between the individual units studied, but also from the way in which factor inputs are lumped together into capital and labour, using the existing factor-price ratios thereby masking the underlying physical relationships between inputs and outputs.

With regard to policy prescription, conclusions drawn from such price based studies, regardless of the level of aggregation, are, in the first place, highly specific to a particular economic environment and, furthermore, are limited by their inability to account for technological differences both in cross-section and in time series analysis.

On a theoretical level, Economists have expressed their reservations on the value of the use of aggregate statistical price-based data to test hypotheses about returns to scale and the elasticity of substitution. Among them, Shaikh[1]

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1 See Shaikh (1974).

was particularly concerned about the way in which the character of the statistical data itself could produce what he described as "the Humbug production function" which was a result of a law of algebra rather than a law of production. He was able to demonstrate how the statistical data used by Paul Douglas (1948), made Douglas' positive conclusions on the constant-returns-to scale hypothesis inevitable.

Shaikh's work shed some light on the way in which aggregate statistical time series data tend to give results which would contribute little to the explanation of the underlying production relations. The actual results obtained could well be simply a reflection of the results of continuous adjustments to prices and market forces.

Kotowitz (1968) noted, too, that the meaning of economies of scale is vague when dealing with highly aggregative relations. He, among others, pointed to the differences between the results from time series and from cross-section data. Walters (1963), also drew attention to the way in which the results of such studies depended on the manner of grouping of heterogeneous units of capital, labour or outputs in aggregate price-based studies.

The concern with the conclusions drawn from aggregate statistical studies are well known and all the contra points need not be reiterated here. The arguments highlight the suspect nature of the results of empirical statistical studies to establish the parameters of production and cost functions, and hence the dubious value of these studies as a basis for policy decisions in industry. The problem is even more acute when the results of studies in one economic environment are applied to practical situations in another.

In sum, then, some of the major difficulties in applying the results of statistical production and cost studies in practical situations stem from the following:

1. The information on factor proportions is really a reflection of the relative factor prices in the economy in which the study is carried out and so are not widely appicable.
2. A single production function is assumed to exist for all firms, industries or sectors covered, as they are supposed to be using the same technology. In this way, the existence of technological differences among firms is ruled out.
3. The data are assumed to represent points on the production frontier - (i.e. all firms are assumed to have adjusted fully to the prevailing factor prices). In reality this is unlikely to be so. Roemer (1972) surmised that the substitution possibilities thrown up by such a study need not relate to the substitution possibilities of a unique production function but might simply reflect the varying responses to market conditions of firms producing with different vintages of technology.
4. No adjustment is made for the under-utilization of capital (or labour) in the plants.
5. The results can show only the productive combinations which have proved feasible in a certain economic context but can not indicate the wider range of productive possibilities not accepted commercially, given the particular

economic environment. Where the data are derived from historical observations the ability to analyse factor substitutability is impaired because of the inseparability of the effect of technological change, price variations, managerial changes, and other environmental changes.

It is against this background that the search for alternative approaches to the analysis of production and cost functions must be seen. Economists have been seeking methods of investigation which would give more meaningful information on the "true" production function, which is, after all, supposed to represent something in the nature of a 'physical" relationship between productive inputs and outputs. On the theoretical level Economists[1] began experimenting with new approaches to the testing of hypotheses about economics of scale and factor substitution, and about technical change. One approach, largely attributable to Chenery (1948), was to use Engineering data to express the "true" physical relationship between factor inputs and output for testing economic hypotheses. Attempts to measure technical developments over any given time period were later made. These studies are examined in Chapter 2 in more detail because of their special relevance to the work in this thesis.

On the practical level, economists concerned with industrial planning and development began seeking alternative approaches to obtaining information on production and cost functions pertinent to their particular concerns about technology choice[2] and factor use and about the employment

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1 See, for example, Chenery (1949, 1953) Vernon Smith (1955, 1957).

2 See, for example, Stewart (1974), Pack (1974).

of labour in particular. The approach here was generally to conduct micro level studies using individual plants as the unit of analysis to avoid the problems associated with the use of aggregated data. The limitations of results based on the use of prices and price ratios existing only in some narrowly defined political or economic entity, and the tendency to consider the alternative factor combinations found to exist in a few plants only, severely restricted the wider applicability of many of these studies. These studies are recounted in greater detail in Chapter 2, and the techniques of analysis are examined in the light of the approach used in this study.

In view of the increasing concern with technological choice in industrial planning, and the gradual recognition of the value of engineering data in giving information on the nature of production and cost functions, factor substitutability and scale, there are obvious benefits to be derived from an understanding of the underlying relationships between inputs and outputs.

One special advantage of the engineering approach is the way in which the overall plant technology can be disaggregated, which in itself can provide useful information to planners, potential and existing industrialists. Without this information, there are often no bases for a rational decision on alternative combinations of the constituent parts of a processing plant which might be considered "inappropriate" in the particular circumstances, if more attractive alternatives were known.

In a study of the food processing sector in the Carribean by the author (Whitehead, 1979), it was found that there was a tendency by the local food processors to import complete plants where the decisions on the "appropriate" combinations had often been made in a different economic context. The producers were generally not familiar with the possibilities for alternative combinations. The results of engineering studies should provide a much more extensive data base for applying criteria of appropriate technology choice.

There is a need, however, for the engineering approach to be applied more rigorously to provide adequate reference data for decision making on Technological Choice. It is useful for the results of studies to have wider applicability and relevance outside of the individual plant and the special economic circumstances in which the study has been done.

It is from this perspective that the work in this thesis must be viewed. The study's point of departure is the current loose link between the formal analysis of production and cost functions done for theoretical purposes, and the more narrowly based practical studies, which have tended to proliferate in the area of technology choice.

The concern for the need for economists to become more involved in the discipline of engineering to derive a better understanding of the technical aspects of the situations they study has been expressed by the Social Science Research Council of Britain[1]. This thesis is a contribution to the movement in that direction.

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1 Social Science Research Council, London, Newsletter "Research in the Economics of Industry and Public Enterprise", June 1981.

1.2 Objectives and Scope

The study sets out to apply the more formal economic analysis, based on the use of a version of the engineering production function, to the problem of technological choice and factor use. The dairy products industry is used to demonstrate the analytical techniques used in this thesis, particularly because it is an agro-industry and has some relevance to economics world wide.

1.2.1 Aims and objectives

The principal objective is to demonstrate the use of engineering data for a more rigorous approach to the selection of alternative plant technologies for an industry. This study sees the major benefits from this approach to be the applicability of the results to a wider spectrum of countries which may desire information on technological alternatives and factor substitutability. The value of the approach adopted will be seen to stem from the flexibility of application offered by the use of data which allows factor inputs to be assessed largely in "physical" terms without being shrouded in the cloak of specific prices and price relatives. Additional economic factors, energy in particular, are now made to figure more prominently among factor inputs.

The aim is to use the engineering data to analyse production possibilities and the relationship between combinations of factor inputs and output, so that the results of the study can have much wider appeal and can be useful in providing a rationale for technological choice in a variety of economic and socio-economic environments. With knowledge of the underlying real relationships between inputs and outputs, and the quantities of factors involved in the alternative technologies described, the factor prices (whether market or social prices) considered appropriate in a particular context, can then be applied.

The study is not designed to be a purely academic exercise, rather, it is intended to provide in itself the type of information useful to planners. The Dairy industry is considered suitable for this type of analysis because of the general important role given to agro-industry in the countries labelled as "developing" where there is usually greater emphasis on the planning of industrial activities.

As a food processing industry, the processing of dairy products, while often being seen as a capital intensive activity, is one that is even more heavily dependent on primary agricultural inputs. As much as 80 percent of the value of some dairy products can be accounted for by the value of the agricultural raw materials (milk). In a study of cost components in dairy manufacturing in a government dairy in India, Somasekhara[1] found that the cost of raw milk was some 60 percent of all costs in the dairy (including sales commission, taxes, etc.).

Underlying the choice of the dairy industry for this exercise, therefore, is the concern with trying to maximize

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1 Somasekhara (1975, p. 575).

the benefits to be derived from the internal operation of the plant by making use of an "appropriate" combination of productive factors.

The study does not aim to discuss which factor combinations may be considered "appropriate" in any given situation, or indeed to make judgements on what type of technology should be "appropriate" in any particular context. The assumption is that within countries, the persons responsible for planning would decide whether market prices or any form of social prices should be applied.

The aim is to have a technique for comparing technological alternatives that is flexible enough to accommodate any new technological developments or any form of "intermediate" special types of technologies developed. By resorting to fundamental engineering principles as the basis for quantifying the physical factors, the analysis can quite easily be extended to other technologies which offer themselves as alternatives.

1.2.2 Scope

The study is limited to the examination of the in-plant production technology options. No account is taken of the product before it reaches the plant or after it leaves. Collection and distribution patterns are highly locational and bear little relation to the choice of technology in the plant. Once the structure of costs and scale and factor use within the plant are known, locational decisions can be optimized taking this knowledge into account.

There are, however, some external factors which have some real bearing on the activities within the plant. The most important is in the reception area. In this study the in-plant reception technology depends, in the first instance, on whether the milk is brought to the factory in bulk tankers or in cans and this in turn depends to a large extent on the character of the supply area (size of farms, distance from the plant, facilities for electricity, etc.).

In order to account for any external factors which may make a particular type of reception equipment necessary, the can and tanker reception equipment systems are not considered as alternatives and the functional evaluation is done for each type individually.

The study is limited to one type of processed milk product - pasteurized milk, but the same type of analysis can be done for the other milk products and also for other food products as well. For most food products the production process involves a number of chemical operations transforming the raw material input into the final product. The basic engineering principles applied in this study (fluid flow, heat transfer, mass transfer) are required for application to other milk and food products. These engineering principles are discussed in Chapter 5.

In selecting a single product (viz. pasteurized milk) the question of product choice for meeting a particular need is not specifically dealt with in this study. If, for example, a need is defined for "milk which has been made free from pathogenic organisms" then the decision of whether to produce pasteurized milk or U.H.T. milk[1] must be made and again factors external to the plant must weigh heavily in the decision. Eating habits and the degree of remoteness of the population would play a much greater role in influencing the choice of the heat transfer process involved at the heating stage in the in-plant process than in-plant cost considerations. The two major heat treatment sub-processes (pasteurization and sterilization) are therefore not regarded as alternatives at that stage in the plant process.

At a higher level, the issue of product choice can be extended to the overall decision on meeting the need for a milk product, less narrowly defined. In such a case the analytical techniques used here can be extended to these other products and comparative studies may be carried out. Chapter 3 provides a general introductory technological overview of the in-plant processes involved in the production of a wide range of dairy products. The scope of the study does not extend to an analysis of the alternative technologies for producing these other products.

In studying the pasteurized product itself, the issue of choice of product characteristics again surfaces, and involves the doctrine of Technological Determinism[2]. This study seeks to eliminate some confusion by refusing to consider as alternatives the different types of technology which produce different observable characteristics in the

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1 Ultra-High-Temperature (sterilized) milk (see Chapter 3.)

2 Technological Determinism refers to the doctrine that once a product is closely specified, the technology required for its production is determined.

final product, and to show the existences of alternatives even where the product characteristics are quite narrowly defined. This is discussed in greater detail in Chapters 3 and 6.

The aim is to describe the relationship between inputs and outputs for as closely defined a product as possible and to avoid taking external decisions into account in the plant functions. The decision to use special alternative inputs to impart certain desired characteristics to the product, depends largely on the tastes and desires of the particular markets served by the plant rather than on any in-plant considerations.

1.3 Approach

Chenery's work on the Engineering Production Function, discussed in some detail in Chapter 2, has been useful in providing some of the basic concepts useful in the construction of production functions from Engineering data. However, because of the dissimilarity of the types of processes being studied, a different approach is required in this case.

By using a single continuous process Chenery was able to assume continuity of the underlying technical law and use the traditional calculus approach to optimization in determining the least cost solution using engineering variables (see Chapter 2). In this case, however, the plant process considered involves several sub-processes, each using different, more complex types of equipment. This type of production technology mix, does not easily lend itself to a straightforward expression in engineering variables (heat, pressure etc.) that can be assumed continuous.

The approach, therefore, is to use the engineering variables to build up to the physical or intermediate variables (equipment, systems, fuel etc.) at the level of the sub-process and to determine overall plant functions by use of the technique of dynamic programming.

1.3.1 The Transformation function at the sub-process level

Following Chenery (1953), production is conceived as the process of energy being applied to materials. This involves investigating what has to be done to the materials inputs possessing certain characteristics, to transform them into an output with its particular characteristics. The different ways in which this can be done must then be explored. This requires the knowledge of certain "design laws" used by engineers, and some familiarity with the engineering principles involved. For this study, a basic understanding of these principles was required and these are discussed in Chapter 5.

Because the aim of this thesis is not to redesign equipment, a continuous function for transformation of material inputs into outputs cannot be assumed. Although there may be endless possibilities for the combination of the engineering variables there are only a few that have been tried. In order to avoid making the results of the study worthless for practical purposes, the engineering variables are used mainly to identify the major component parts of the physical systems to which costs can be attached.

The physical alternatives are identified in Chapter 6.

The primary unit of analysis is closely related to a unit operation of food engineering and it is on this basis that the plant process is disaggregated. These operations have been listed in Chapter 3. The grouping of operations has been modified to take into account the special combination of activities in a pasteurizing plant.

This production model may be described as inclusive rather than aggregative. Although the model is essentially static, it differs from the traditional aggregate statistical model in that it is not assumed that there is a single technology used by all firms. Instead, the model considered that at any one time there is a range of technologies available which can be selected by any of the firms, and that these technologieal alternatives at the sub-process level can be combined at the plant level in various ways, many of which may not actually exist in any plant currently in operation, but is technically feasible. The production function may then be thought of as expressing the production potential of a well defined industry or part of it, in this case, the pasteurized milk industry. Chapter 6 identifies the physical alternatives at the sub-process level. Once the alternative factor combinations at this level have been identified the analysis can then be taken to the level of the plant as a whole.

1.3.2 Plant level analysis

In order to take the analysis from the sub-process to the plant level some method must be found to take into account the interrelationships between the sub-processes. In many of the studies discussed in Chapter 2, the assumption of complete independence of the sub-processes was made and, in order to develop plant level functions, the optimal results at the sub-process level were simply combined.

In this thesis, however, use is made of the technique of dynamic programming to take account of the influence of choice, at one stage in the process on the choice at the other. Chapter 4 discusses the dynamic programming technique and the way interrelationships between stages can be taken into account.

In using this technique to consider the overall cost function at the plant level, the variables are allowed to remain in the physical form with the factors expressed in a form to which costs can be applied (e.g. steam quantity which can be converted to fuel requirements and costed). The computer optimization programme has been designed so that any set of factor prices can be established as parameters at the start of the run and the overall cost optimization done by the recursive procedure of dynamic programming. In this way, the effect which choice at one stage has on the costs of making choices at another stage can be taken into account. This optimization is done in Chapter 7.

This new approach to plant level optimization in technology studies, combined with the expression of the production function in physical variables based on engineering principles, is what gives the approach used in this thesis, its peculiar flexibility for wider applicability of the results. The price parameters can be varied for any economic environment. The basic physical factors identified and based on engineering principles, are applicable wherever the particular processing alternative is used (e.g. steam requirements for effecting a certain heat transformation of a product depends on certain thermodynamic laws (heat transfer) which would apply whenever the same equipment system with the same given design was being used).

As new technologies are developed these can be included and the transformation function would reflect the range of possibilities for the pasteurized milk industry at a given point in time, taking into account older vintages of technology which are still currently available and which may be useful when certain factor price ratios are set as the run parameters.

1.4 Research Strategy

A substantial amount of information gathering has had to be done. In the first instance the technological structure of the pasteurizing industry had to be investigated and the general processes understood. The underlying engineering principles had to be assimilated and the physical alternative systems identified and their factors quantified for analysis. The following strategy was adopted.

The initial step was to use texts on food engineering and on dairy process engineering in particular, to achieve the level of familiarity with the in-plant activities which a study of this nature required. Trade and business journals[1] were a good source of the basic technological information required. Information on unit operations in food processing and on the nature of the operations in the dairy processing plant was reasonably accessible[2] (see Chapter 5).

At the next stage the strategy was to consult with dairy equipment manufacturers to obtain at first hand information on the current alternatives available, and to learn as far as possible the nature of the inputs required for the use of the equipment. The type of information which was sought from manufacturers in personal interviews is described in Chapter 5 and the questionnaire used for recording the information is included as Appendix 5.1.

In addition, the research strategy included visits to dairy plants in order to acquire first hand knowledge of the ways in which alternatives have been combined in the plant and to observe the performance of the equipment designs in the actual plant setting. The questions asked on these visits are discussed in Chapter 5 and the details of the questionnaire used are included as Appendix 5.1.

The above sources have been valuable in providing a wealth of information on the alternatives available. The scope of the research can always be extended to cover other forms of equipment systems and processes not included here and which may be peculiar to certain isolated areas of the world. They, too, can be included in the analysis and their

1 Including the Journal of the Society of Dairy Technology, Journal of the Food Industry - Food Manufacture; Dairy Engineering; Journal of Food Technology.

2 See especially Browne (1950); Farrall (1963); Lampert (1970); Harper & Hall (1976).

suitability for various factor price combinations assessed in the overall plant optimization procedure.

1.5 Plan of the Thesis

Chapter 2 is a survey of the related studies done so far on the engineering approach to production and cost functions and on technological choice. The pioneering work of Chenery which inspired this thesis and the early studies involving the use of engineering data as a basis for empirical economic analysis, are examined in the first part of the chapter.

In view of the emphasis on technological choice in this thesis, the studies done in this area come under some scrutiny in the latter part of Chapter 2. The approaches, techniques and results of these studies are analysed and assessed in the light of the particular strategy used in this thesis.

The chapter shows the trends in the more formal engineering studies, concerned primarily with answers to theoretical questions, and the gradual incorporation of the engineering approach in the technology studies concerned with finding practical solutions for the more mundane concerns of development planners, such as employment and factor use. This thesis is seen as the culmination of this process of synthesis where a more rigorous engineering production function type of approach is used for answering questions on technology choice.

A general overview of the technology involved in the dairy industry is provided in Chapter 3, as an introduction to the nature of the processes and alternative equipment systems used in the wider dairy products industry. This preparatory study paves the way for a more in-depth analysis of the technological structure of the pasteurization process which is the subject of investigation in this thesis.

Chapter 4 is devoted to a discussion of the Special Dynamic Programming technique which is used for the plant level optimization process. The chapter examines the procedures involved in the application of the technique and assesses its special suitability to the type of technological optimization required, given the structure of the process in the pasteurizing plant.

The wealth of technological information required and the type of engineering principles with which a researcher involved in this type of study must be acquainted are revealed in Chapter 5. The principles explained in some detail in this chapter are those which have had to be applied to some extent in the preparation of the data included in this thesis.

These basic engineering design laws in thermodynamics and hydraulics in particular, are basic to understanding and quantifying the physical input requirements of a processing alternative.

The quantification of the physical variables is done in Chapter 6, with reference to the individual groups of subprocesses identified in Chapter 3. The alternative technologies available and the relative factor proportions required are evaluated and compared. This chapter describes, in essence, the nature of the "underlying" production function which is considered to be so elusive when aggregate statistical price-based data are used.

Chapter 7 deals with the overall plant level optimization for which the Dynamic Programming Technique is used so that the interrelationship between choices at the different stages may be taken into account. In this chapter the flexibility of the approach used is illustrated by the way in which the nature of the basic data used and the optimization technique, in conjunction with each other, facilitate the design of a computer programme which allows any set of factor price relatives to be plugged in to obtain the appropriate results.

The optimization technique used allows the easy identification of the appropriate choices at each stage of the process when the overall optimal (least cost) solution has been found.

The implications of the results for the hypothetical economies are discussed in Chapter 8. The possibilities for expanding the analysis into the more formal areas of economic theory are explored. General conclusions are drawn about the approach used in the study and the nature of the results obtained as a basis for a comparative evaluation of this approach and the price-based statistical alternative.

CHAPTER 2

THE PRESENT STATE OF RESEARCH

Several economists have undertaken micro studies of plants and processes using basic data of an engineering nature and, in some cases, using an approach which borders to some extent on the concept of a production function.

In this chapter, the literature is surveyed, and the more relevant works in this area are examined to assess the state of the research in the field so far and to indicate the way in which the approaches used in these studies are considered deficient in meeting the particular aims and objectives of this study, as spelt out in the previous chapter.

The chapter begins with an examination of the engineering production function concept, and then proceeds by studying the ways in which it has been applied initially. The chapter then focusses on the later developments and on the studies which have proliferated in the area of technological choice, illustrating how the use of engineering data gradually crept into the studies.

This survey indicates the way in which this study attempts to advance the methods used in considering technological choice by using a more rigorous approach via the engineering production function.

2.1 The Engineering Production Function

Before proceeding further, it is imperative that closer attention be paid to the concept of an engineering production function to avoid any misinterpretation of the term or misunderstanding of the nature of the exercise.

The fundamental difference between the engineering and the economic production functions lies in the basic units used. The engineer deals with separate physical processes and is concerned with pieces of equipment and variables such as size and temperature. The economist is concerned with plants, firms, or industries and with broader, more encompassing variables such as capital and labour.

Normally, after the engineer has worked out the combinations of inputs with the least cost, the economist takes the resulting quality and types of inputs as parameters. The engineer, however, does not have the leeway to reserve all cost calculations until all the possible physical combinations of inputs have been considered. Thus in order to construct an engineering production function, the economist must go back to the intermediate stage in the engineering calculations and consider the possibilities of using various types of inputs.

It is recognised generally, that in using statistically derived production functions, the results show only the productive combinations which have proved feasible but do not indicate the wider range of productive possibilities not accepted commercially. This impairs comparison of factor substitutability because, in the observed data, the effect of technological change and price variations are usually inseparable. In addition, the implicit assumptions that firms are operating on the production frontier and at full capacity with total X-efficiency are wholly unrealistic. It would, therefore, be unwise to attempt to apply such results to industrial planning in a small developing economy.

It is important to be aware of the limitations on the ability or ease of construction of these engineering production functions. These limitations partly relate to the fact that engineering is concerned mainly with machines rather than men (capital rather than labour). The construction of these functions requires quite in-depth knowledge of the engineering principles involved.

Chenery (1949) lists the three best cases for the construction of engineering production functions. According to him, the favourable cases are those in which:

i) labour can be treated as a joint factor with some other input,

ii) engineering science is well developed,

iii) the technical characteristics of one or a few principel processes are a determining factor in the cost structure of the plant or firm.

Thus he considers the most suitable industries to be those involving chemical processes, the refining of raw materials and those using other standardised automated techniques.

It may be pointed out, however, that with expansion of the capabilities of the computer since 1949, and the further development of other useful techniques (simulation, dynamic programming, etc.) some of the previous limitations are now less restrictive on the types of production processes that can be handled.

Using the engineering approach, the variables for this type of analysis may be separated on three levels and dealt with at these levels individually. At the end, the final (highest) level of variables is that of the broad economic factors of production (land, capital, etc.). The intermediate level variables are the physical inputs or purchasable commodities (types of machinery, equipment, fuel, etc.), which are considered to make up the broad factors of production described in the higher stage. At the lowest level are the engineering variables which express the physical properties or dimensions of the inputs described for the intermediate level.

It is important that the engineering variables be seen to determine the quantity and the cost of the physical inputs chosen at the intermediate level (e.g. where the physical input is a machine, the engineering variables may be size, speed, continuity of operation, etc.).

The basic procedures involved may be demonstrated for a single, continuous chemical process, such as the one considered by Chenery (1949).

The build up to the economic production function can be done by transformation of the engineering variables.

i) Firstly the physical inputs are expressed as a function of the engineering variables:

$$I_i = I_i(E_1, E_2, \ldots, E_n)$$

where I_i is the quantity of each physical input, and

E_i is the engineering variable.

Also,

$$P_i = P_i(E_1, E_2, \ldots, E_n)$$

where P_i is the price per unit of I.

From this, the regular economic production function may be derived:

$$Q = Q(I_1, I_2, \ldots, I_m)$$

where Q is the output per unit of time (or capacity of the process).

It is therefore possible to write an expression for the engineering production function in this way:

$$Q = Q(E_1, E_2, \ldots, E_n)$$

by expressing the I_i's in terms of the E_i's.

The standard economic total cost function can be similarly transformed to use the engineering variables. Instead of writing

$$C = \sum_{i=1}^{m} I_i P_i$$

one can write

$$C = \pi(E_1, E_2, \ldots, E_n).$$

Thus both quantities and costs are functions of the engineering variables.

From here the conditions for equilibrium are the same as with the economic variables and Chenery uses the standard text book approach.

Cost minimization with a given output $\overline{Q}$ may be done as follows:

Using Lagrangian multipliers:

$$Z = \pi(E_1, E_2, \ldots, E_n) - \lambda\left[\phi(E_1, E_2, \ldots, E_n) - \overline{Q}\right]$$

A relative minimum is obtained where

$$\frac{\delta Z}{\delta E_i} = \pi_i' - \lambda\phi_i' = 0 .$$

Thus obtaining,

$$\frac{1}{\lambda} = \frac{\phi_i'}{\pi_i'} = \frac{\phi_2'}{\pi_2'} = \ldots = \frac{\phi_n'}{\pi_n'} .$$

Thus the marginal productivities of the engineering variables must be proportional to the marginal costs for each variable.

These n equations, plus the equation:

$$Q = \phi(E_1, E_2, \ldots, E_n)$$

determine the values of the n engineering variables (and of λ), which will produce a given output $\overline{Q}$ at least cost.

These are the necessary conditions for the minimum. The sufficient conditions are, as usual, fulfilled if the isoquants, in terms of the E_i's are convex to the origin in all directions.

It is then possible (though difficult) to carry out the usual economic analysis with the variables transformed from the engineering stage via the physical inputs to the generalised factors of capital and labour. It is possible to test directly for the shape of the production function and to examine economies of scale and elasticity of substitution between the broad categories of factors by making full use of the engineering data and building up through the intermediate physical variables. It is likely that the final production function may involve different processes over different ranges of output.

The main advantages of this type of approach lie in the lesser susceptibility of the data to the biases and extraneous influences which affect aggregate statistical data. It can therefore be of greater value in production planning. The economist is no longer simply describing the results of a series of historical observations containing the influences of price changes, managerial changes and other types of technical and environmental changes.

Chenery (1949) illustrated his technique with an analysis of pipeline transmission for gas production -- a continuous flow type of process. With a homogeneous product (gas) as the output, knowledge of the technical relations would indicate the relevant engineering variables. For example, it is known that the quantity of gas transmitted by pipe depends on the diameter of the pipe, pressure of the gas and the pressure drop along the line. From this one knows that capacity can be increased by increasing the diameter of the pipe, its thickness or the pumping capacity. Using Weymouth's formula relating output to pressure and diameter

$$X = KD^{8/3} \sqrt{P_1^{2} - P_2^{2}}$$

it becomes possible for him to write the gas flow in terms of pipe diameter and pressure. Then, making use of the known properties of pipe and pumping engines, relating pressure of pipe (P_1) to stress and thickness of pipe (ST) and to diameter (D), it was possible to use the formula ($P_1 = \frac{2SD}{D}$) to convert pressure (an engineering variable) into physical variables (pipe thickness and diameter).

As a result, gas output could be related to physical inputs such as thickness and diameter of the pipe and the spacing of compressor stations (pressure).

From this point more routine methods were used to examine the nature of economies of scale after deriving the cost function. Cost was considered in terms of annual charges on installed equipment (interest, depreciation, property taxes and obsolescence), with annual operating costs depending on the quantities of several capital goods installed, and other operating costs.

With this particular type of production function, factor substitution was only possible between compressors and pipe. The amount of fuel and labour used was determined by the size and amount of capital equipment used (pipe and compressors). The raw materials (gas, etc.) were only used as fuel during the process. Cost analysis proceeded along the text-book lines with the engineering variables being substituted for the physical ones (since they determined the physical ones). In this way, the minimum cost solution could be found and the effect of price changes on the least cost position computed.

In using a fairly straightforward continuous flow process, Chenery was able to avoid all the complexities involved in working with the type of product which required different types of separate and discrete processing activities at different stages of production. The analytical method described here cannot be used with such facility when the manufacturing process involved consists of a number of sub-processes. This is the case in the dairy process analysed in this thesis. The major complication stems from the more complicated designs of the equipment available (unlike a single pipeline) which increases tremendously the task of expressing the designs in terms of the engineering variables. Furthermore, owing to the limited designs of equipment available, conclusions reached from reference to smooth and continuous engineering functions as described above, would lead to the consideration of many non-existent alternatives.

The major work by Chenery, did, however, provide a basis for a new approach to the empirical determination of production and cost functions which now appears to be a potentially valuable source of help to planners of new manufacturing activities.

In this thesis, a modified approach is used, so that the underlying engineering relationships in a production plant can be used to derive production and cost functions for more complex processes and to give more information on actual technological choices available in physical terms to planners interested in the solution of alternatives for new manufacturing plants.

The major difference is in the role played by the physical (or intermediate) variables, which are more easily identifiable, and which can be made to relate to the economic costs which a manufacturer faces. This is mainly because the underlying relationship between the engineering variables and the costs attached to the physical variables may not always be consistent.

This study therefore uses engineering variables in deriving physical variables, but then analyses the relationships between inputs and outputs for only the physical alternatives that have already been designed. In this way no redesigning of equipment is necessary and economists can have far more insight into the real economic choices than would be possible with aggregate statistical analyses. Costs appropriate to any economic situation can be attached to the variables derived from the engineering analysis (steam, electricity units etc.).

The way in which Chenery's approach has developed is of some interest, and this is examined below. Of particular relevance is the nature of the progress made in studies on technological choice. These studies are subjected to scrutiny.

2.2 Developments in the Field

The engineering approach to production and cost functions has been developed in many directions over the decades. But out of this there has failed to come any standard techniques for deriving useful results from engineering data in a way that would encompass wide and varying industrial conditions and product types. This is mainly because many of the studies have generally not been concerned too much with methodology and the formalization of techniques and so have tended to remain as isolated case studies.

A closer look at the studies done using micro and engineering data would illustrate the types of advances made and also the limitations of the various studies. This review of the literature should help to put this proposed study in its proper context. The studies and their contributions may be classified in terms of their different emphases. These may be identified as follows:

1) Studies of continuous flows and chemical processes.

2) Input-output engineering studies.

3) Studies of operations and tasks.

4) Technological progress studies.

2.2.1) Studies of Chemical Processes

There was some interest in Chenery's approach for a while after his 1949 article and thesis in 1950. These studies mainly continued along the same lines and were concerned with the physical explanations which this approach provided for the phenomena of economies of scale and factor substitutability in particular. The studies continued to examine the continuous flow and chemical type processes.

The first noteworthy study of this type was by Cookenboo (1954) in which the cost of operating crude-oil pipelines was investigated. This is the only well known study during that period, which, like Chenery's, was developed from the engineering bases through physical variables to economic variables. The study was developed to the extent of providing the text book type isoquants, expansion paths and cost curves.

During this period there was some interest in engineering production functions at the Massachusetts Institute of Technology (MIT), and this was revealed in two unpublished Theses by C. Campbell (1959) and L. Eng (1960). The technology of Electrolytic Chlorine Manufacture studied by Campbell and that of the fluid catalytic cracking process done by Eng were the types of chemical processes more amenable to engineering analysis. The MIT studies, however, did not go as far as the two earlier studies mentioned, in developing their work up to the cost curves and isoquants of the textbook microeconomic theory.

Around this same time, Frederick Moore (1959) published his work on economies of scale using engineering data. Moore was mainly concerned with the application of the '.6 factor' rule which relates to the fact that the cost of an item is frequently related to its surface area, while the capacity of the item increases in accordance with its volume.[1] This approach by Moore diverged somewhat from the continuous type flow analyses by Chenery and Cookenboo by considering costs in relation to separate pieces of equipment. It was an application of an engineering 'rule of thumb' to explain economies of scale for pieces of equipment.

Moore recognised that even though the rule may in fact be valid, it could be applied mainly to pieces of equipment but could not be applied in the same way to a whole plant with various types of components. The work suggested that economies of scale would be limited to specific congeries of equipment. In this way, it did not represent any significant advance in the use of engineering functions.

2.2.2) <u>Input-output engineering studies</u>

During the 1950's attention was also being paid to the use of engineering data to assist in the determination of the technical co-efficients for use in Input-Output analyses. The term 'process analysis' was used in this connection to refer to the formal analysis of industrial production processes.

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1 The '.6 factor' rule derived by engineers is a rough method of measuring increases in capital cost as capacity is expanded. The rule says that the increase in cost is given by the increase in capacity raised to the .6 power or that

$$C_2 = C_1\left(\frac{X_2}{X_1}\right)^{.6}$$

where C_1 and C_2 are the costs of two pieces of equipment and X_1 and X_2 are their respective capacities.

Models based on relationships known to the engineer were used in this connection to answer questions concerning to the product mixes available with various combinations of resources in an economy. It was felt that process analysis could be used at industry-wide and multi-industry levels and could be expanded to economy wide studies. This possibility was examined by Markowitz (1956).

This use of process analysis for Input-Output is generally associated with the Harvard Research Project on the Structure of the American Economy, and the studies in this area are published in Leontief et al. (1953). The use of engineering data in this regard is the subject of articles by Chenery, Holzman and Anne Grosse of the Harvard Research Project and by Allen Ferguson (on air transportation).

The analysis of processes was being done to estimate industrial capabilities at the level of particular plant operations (e.g. Blast furnace capacity, metal machining operations), in contrast to other capability indicators such as Inter-industry sales and purchases, and G.N.P. analysis.[1] The process analysis is closer to a requirements analysis.[2]

The main advantages of the use of engineering data and process analysis in the context of Input-Output analysis stem from the ability to distinguish between alternate ways of producing the same product. Thus in a capability analysis of an economy it is possible to consider the use of different

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1 GNP analysis estimates the total GNP required to meet a proposed economy-wide program and compares this with the GNP which the economy is likely to have at its disposal.

2 In a Requirements Analysis, the total of some specific material(s) required as the input for a particular project is computed and this figure is compared with the projected availability of the particular material input(s).

processes because of the relative scarcity of one resource to the next. In practice the choice of production methods depends on relative scarcities of certain resources, and thus the coefficients of requirements analysis depend on the very shortages and surpluses to be predicted.

In this connection, engineering data were used, not strictly to supplement or to test existing microeconomic theory but to determine the relation of physical inputs to physical outputs and to assess the reaction of the Input-Output co-efficients to alternative technologies which could be used in the various industries. This would include a study of labour use and labour substitutability in a closed Input-Output model (a model including the household as an industrial sector).

A number of studies done in this period were presented at a conference sponsored by the Cowles Foundation for Research in Economics at Yale University in 1961, and are collected and edited by Markowitz and Manne (1963).

In his study of the Petroleum Refining Industry in the U.S., Manne used a detailed engineering analysis which was aimed at alleviating certain rigidities in the standard Input-Output analysis.

Thus the benefits of the use of engineering data for providing greater flexibility in empirical economic analyses was being gradually recognised.

2.2.3) <u>Studies of 'operations' and tasks</u>

Kurz and Manne (1963) introduced a novel feature in their study of capital-labour substitution in Metal Machining, by measuring output in terms of the number of operations that could be performed on a particular machine during a work day. Prior to this, the methods used made it difficult to handle anything outside of the chemical industries and those involving continuous flow processes.

Kurz and Manne were concerned with the number of 'tasks' which could be performed by a single machine and these tasks when quantified were used as the physical measure of output from the machines. Capital (the machines) was also considered measurable in physical units (labour is accommodating). In estimating the functions, dummy variables were used to take account of the differences between output tasks. Markowitz (1955) had previously analysed the metal working industry in a Rand Corporation paper and, together with Rowe, had done an analysis of Machine Tool substitution possibilities. (Rowe and Markowitz, 1955).

Kurz and Manne (1963) had however, made the error of not annualising (or in this case diurnalising) the capital costs of the various machines, and used only initial investment outlay as the criterion for judging machines by their efficiency. Thus where machines were producing the same daily output but had different initial cost, those with the higher initial costs were eliminated as inefficient. The flaw in this is that the machines with higher initial investment cost could have had a longer life which would not have been taken into account.

Furubotn (1965a) expressed the view that a major problem with the work my Kurz and Manne was their use of prices (of machines) to define a production function. He suggested they should have kept to the use of physical terms or should have used 'objective physical criteria'. Lave (1966) pointed out, however, that technological relationships cannot be kept so pure. Because of the large set of possible input combinations, some of the alternatives must be ruled out, and this must be done by assuming a set of prices.

Later studies have continued to use prices to measure capital, but have generally preferred to use some kind of discounting procedure to derive present values. In a straightforward optimization procedure, the prices chosen are very important in determining the particular economic situation in which the optimum holds. The approach used in this thesis helps to overcome such rigidities by focussing directly on the physical factors derived from the engineering functions, so that any set of price relatives may be applied to suit the prevailing economic conditions in any particular context.

Another important contribution to the analytical study of processes was made by G.K. Boon (1964), in his work on the economic choice of human and physical factors in production. In his attempt to measure the micro- and macro-economic possibilities of variations in factor proportions of production, he was able to show an appreciation for the dimensions and complexities of actual productive operations. The technological characteristics of woodworking, metalworking and earthmoving operations were examined.

Boon was seeking a method which would be well adapted to empirical investigation and which could be used to determine meaningfully the optimum, or least cost, technique for producing any commodity. It was recognised, then, that this type of factual information concerning technical alternatives was essential to the furtherance of the goals of development planning in developing countries. His primary concern was with the choice among production processes of different capital intensities.

Some important insights are provided by the study. In particular, the study shows some concern for efficiency and addresses itself to the issues of lot size, the concept of capacity, the influence of machine design and working capital requirements. His cost functions show how costs vary from one process to another and from one level of output to another. It is the knowledge of the pattern of intersection of these cost functions that allows a firm to select the 'optimal' process to produce any stipulated output.

Unfortunately, however, Boon does not make real use of the production function concept, a fact which Furubotn (1965b) thinks makes Boon's analytic position difficult to interpret and causes him to lose the opportunity to link his study with the growing volume of literature on engineering production functions. The trouble stems mainly from his framework of analysis. Information is provided on the physical amounts of the factors used and the expenditures made on them, but there is no explicit indication of the way the physical inputs are related to output. Thus he has really ignored the production function.

Despite Boon's awareness of the complexities of production, there also appears to be some oversimplification of matters in his assumption of a limited number of productive processes based on fixed technical coefficients. Thus the choice is made between input sets which are separate and distinct rather than between sets having different proportions of the same types of capital equipment and labour.

The tendency to assume a limited number of productive processes is also found in many of the later studies on developing economies. While it could be useful in aimplifying the analysis, it is doubtful whether it does allow very meaningful conclusions to be drawn by those interested in planning production. The proposed study seeks to avoid some of these pitfalls and to develop a methodology that is applicable in widely varying situations.

2.2.4) Technological progress studies

The bulk of the studies using engineering production functions have tended to concentrate on using engineering data to assist in the analysis of economies of scale and of factor substitutability. There were some, however, who felt that engineering data might be useful in another area of microeconomics where the results of empirical studies left some nagging doubts - the analysis of technological change.

Vernon L. Smith (1955) explored this avenue in a hectographed paper from the Harvard Economic Research Project entitled "On the Use of Engineering Data and Direct Statistical Techniques in the Analysis of Production and Technological Change'. Smith used engineering data to analyse production and technological change with respect to fuel requirements in the trucking industry.

More recently, T.G. Cowing (1970) also used an engineering approach to the study of technical change in steam-electric generation, in an unpublished Ph.D. dissertation at the University of California, Berkeley. Around the same time, D.J. Pearl (1971) did an economic analysis of the progress in crude oil pipeline technology during the period 1952 to 1969 in an unpublished thesis at Oxford University.

Later, D.J. Pearl and J.L. Enos (1975-76) published their work on Engineering production functions and technological progress. Like the majority of known studies using engineering data to measure technical progress, the analysis relied heavily on engineering data provided by earlier studies of the same industry. In this case Pearl and Enos studied change in the transport of crude petroleum by pipeline, basing their analysis on the work done by Cookenboo (1954) some seventeen years earlier. Their method was to use the information provided by Cookenboo, and, keeping inputs and outputs constant, they varied only the technology. They then compared the two sets of results and tried to isolate the difference.

This study, like most of the others on technological change, did not introduce any strikingly new techniques or analytical developments in the use of engineering data or the derivation of engineering production functions. This was largely because they tended to use the results of studies already done, and, particularly in the case of Pearl and Enos, the industry chosen was one which involved the analytically simpler continuous flow type of processing activity.

2.3 Trends in the Studies on Technological Choice

The concern of developing country policy makers with the employment problems of industrialization in particular, and with the emphasis on choosing 'appropriate' technology, has led to an increasing interest in the use of engineering data in production studies. There has been a proliferation of micro studies on technological alternatives which have ranged from plant level studies to studies at the level of sub-processes, and have been gradually approaching the engineering production function type of study.

This study is particularly concerned with the development of an approach to the empirical determination production and cost functions that would be of value in informing the decisions on technological choice in as wide a range of economic regions as possible. It is useful, therefore, to examine the state of the work done, so far, in this area.

Among the earlier studies were those by A.S. Bhalla (1964, 1965) on technological choice in cotton spinning and on the choice between handpounding and machine milling of rice in India, respectively. Bhalla emphasized the need for joint optimization of a triad of objectives - output, employment and reinvestment funds - from a given investment, at a time when employment was often considered the sole objective. His main interest was therefore in considering statistical ratios - output ratios, employment ratios and the ratio of reinvestment funds to the sum invested in the project.

Most of the more familiar studies on technological choice in developing countries came almost a decade later (1974 onwards) and can be categorised as follows:

1) Plant level studies.
2) Sub-process level studies.
3) Engineering type studies.

2.3.1 Plant level studies

Some of the earlier studies on technological alternatives tended to concentrate on a few of the existing combinations of sub-processes as observed in plants in various economies. Thus although attention was given to the technical features of the different technologies used in these plants, the analysis was at the plant level with statistics being gathered on the performance of the overall plant technology in use.

In this way, very little engineering data was needed, and these micro studies took as given the choices already made by engineers at some time in the past in the determination of the type of technology being used in the respective plants.

A study of this nature was done by C.G. Baron (1973) on sugar processing techniques in India. His aim was to discover whether large- or small-scale technologies for making sugar were more appropriate for the manufacture of sugar in India. This study, like many others on appropriate technology, was concerned primarily with the question of employment in plants and so appropriateness was measured in terms of the employment/output ratio existing in the respective plants observed.

In doing this, Baron neglected the possibilities of choices at sub-process level and went ahead and made a comparison between two complete sets of techniques existing in two separate existing plants - a small scale 'intermediate' technology for making white sugar, and a larger and better established capital-intensive process. In doing this, Baron was analysing the results of only two of the possible combinations of sub-processes that could have been devised.

One of the main inadequacies of this type of study is that it takes for granted what exists, and, to the extent that conditions may not be optimal in each plant, there could be many distortions which would lead to inaccurate predictions from the results of the study. Baron, himself notes, that each sugar mill (plant) operated with varying technical efficiency and different schedules of costs. Furthermore, government controls and restrictive labour practices that applied in the Indian capital-intensive (large-scale) sector, did not apply in the smaller scale sector. Thus the use of these prevailing prices in each sector renders the results virtually useless outside the particular Indian context. The range of applicability of the results of the study was therefore quite restricted.

A similar micro retrospective study of existing complete technologies was done by C. Cooper et al. (1975) on can-making in Kenya. Their approach to choice of technique was to examine whether those actually in use for making various types of cans in Kenya, Tanzania and Thailand, were economically efficient in relation to one another. This efficiency was measured in terms of output per worker and output per unit of capital installed.

They acknowledged that different choices could be made at different stages of production, but the quantitative data covered the production line as a whole and was not disaggregated to the sub-process level. For the products examined (kerosene tins, open top cans, shoe polish tins), three, four and two existing complete technologies were used respectively, for comparison. Some of these lines were fully mechanised, others automated or semi-automated.

Conclusions were being drawn from plants operating at different levels of capacity and with varying labour and capital intensities. Again it is difficult to draw conclusions for wider applications, from this type of exercise. They did, however, arrive at the interesting conclusion that choices of technique are not highly sensitive to factor and unit cost, a conclusion supported by Pickett (1974) in his study on the choice of technology, economic efficiency and employment in developing countries.

2.3.2) Sub-process level studies

The importance of technological choice at the sub-process level was gradually being acknowledged. However, some of the studies in this area tended to examine the sub-processes and to leave the analysis at this level. Other studies made simple links to the plant level without fully taking interrelationships into account.

a) Studies of individual sub-processes

In a study of cement block manufacture in Kenya, Frances Stewart (1975) examined the alternatives at sub-process level.

Again the focus was directed to employment of labour and each sub-process alternative was scrutinised to determine the ratio of the number employed to the investment in plant. The output/investment ratio was also computed. There was, however, no attempt to rigorously combine these sub-processes into a full scale plant technology, and the production function was therefore not defined.

In studying technological choice in Metalworking in Mexico, G.K. Boon (1975) undertook a task-level analysis[1] of the industry. The unit of analysis was individual machines that could perform certain tasks, and efficiency was measured in terms of handling and machining times. In this discrete type process industry, calculations were made on the basis of machine utilization expressed in production hours and not in physical output quantities. Annual capacities of installations could not be measured in physical terms as in flow process industries. Lot sizes and utilization levels of equipment were expressed in hours and the technology with the lowest unit cost was regarded as being the optimal one for a fixed and given task.

Again, however, the production function was not fully defined. There was no serious effort to link inputs with outputs beyond the level of individual tasks. This was partly because, as Boon pointed out, the data was 'process oriented' rather than 'product oriented' and so concern for optimality was expressed only at the level of each task.

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1 By 'task-level analysis' Boon refers to an analysis of the performance of different types of machines that can be used for certain basic operations (tasks). A task is an elementary machining operation defined for a particular type of metal, in terms of precision and the shape and size of the work-piece.

This study was closely related to Boon's 1964 study on economic choice of human and physical factors in production, discussed earlier. Much the same criticisms therefore, apply as before. Similarly, many of the more favourable comments apply equally in this case. His approach to sensitivity analysis is quite useful for further studies. The approach was to distinguish between two classes of parameters -- economic and physical -- and a sensitivity analysis was done to assess the effect of discrete variations in the main parameters (e.g. lot sizes, wages, utilization levels of equipment, etc.). He pointed out that it was not only necessary to know how optimality was influenced by the variation of the parameters but also how each parameter independently influenced optimality.

b) <u>Sub-process level studies with simple links to plant level</u>

Uhlig and Bhat (1977) moved towards the linking of sub-processes to plant level operation in their study of the choice of technique in the maize milling industry. They pointed out that the available choices were to be assessed by means of an economic appraisal of <u>model</u> factories, and it was not to be a retrospective evaluation of existing factories.

The physical parameters for the models were based on observation and measurement undertaken ex-post at existing maize and wheat mills in Europe, Africa, the U.S. and Asia. These physical parameters included scale of operation, yield and specification of the finished product, power consumption, and spares and maintenance. The level of labour intensity was assumed to be that of the 'best-managed' mills in Kenya.

The aim of the study was to show that choosing between different bits of equipment is one way of reducing investment costs and modifying labour intensity - labour intensity being measured by the ratio of present value wage costs to present value investment costs. The stages in production were considered in some detail separately and then four possible combinations of sub-process equipment were considered. These involved combinations of European and Indian equipment for core and ancilliary operations. They came to the well accepted conclusion that, even with apparently rigid core processes, there may be considerable scope for varying factor proportions if alternative sources of equipment are explored.

The study is restricted by the choice of only four combinations of processes to make up complete technologies. The concept of the engineering production function is not used in this case and the micro data hardly deal with engineering variables as such. The data start at the level of the physical variables and the information is limited to the particular machines and combinations of equipment components as they exist in the factories studied.

Other studies were done in which sub-processes were examined in detail and attempts made to link sub-processes together to form a complete technology, but which did not really use the production function concept to any great advantage. Two of these studies sought to derive the optimal (lowest cost) technique for each sub-process and then to link up the low-cost optima to derive the plant optimum. The studies referred to are those by Bhat and Pandergast

(1977) on technology choice in the Iron Foundry industry and by Keddie and Cleghorn (1977) on the Brewing industry.

Bhat and Pandergast (1977) looked at three key sub-processes in the Iron Foundry industry: a) sand preparation, b) melting and c) moulding, and examined the effect of wage rates, discount rates, scale and quality standards on the techniques to be used. Their aim was to see how these factors (wages, etc.) affected the extent to which labour-intensive processes were used. All the analysis was done at the sub-process level. Their procedure was:

1) to compare costs of alternative technologies at each independent sub-process level,
2) to combine the sub-process optima as defined by the least cost technique at some set of prices, to yield optimal plant technology.

It is not likely that the sub-processes could be so totally independent that choice at one stage would not affect the other. The authors recognized this but noted simply that where less than complete technological independence prevails, the scope for combination may be reduced. They do not, however, deal with this explicitly and so once again the true complexities of actual plant operation are not fully discussed.

The study by Keddie and Cleghorn (1977) used a similar method of analysis. The motive behind the study was, however, different from the Bhat and Pandergast study. In this case the authors were trying to test the hypothesis that, given low wage rates in developing countries, the use of technologies which use much labour would result in lower costs of production.

The authors made a comparison between 'turnkey' technology[1] (which is generally considered capital intensive, high cost and inappropriate in LDC's) with what they called 'least cost technologies'[2]. The analysis was carried out using market prices because of their scepticism about the significance of social prices.

The least-cost technique at each stage was determined and the least cost overall plant technologies were derived by combining the techniques found separately to be least-cost at each stage of the production process. The least-cost technology was then compared with the 'turnkey' technology in which a specific set of techniques were used which were invariant to the particular local circumstances.

This type of analysis was therefore not much more advanced than the sub-process and task-level analyses of Boon and Stewart. The efforts to relate inputs to output and to derive a schedule of costs for a complete technology did not, again, take into account all the complexities involved in the combination of techniques at the different stages.

2.3.3) Engineering-type studies

Some studies moved closer to the concept of an engineering production function and tried to use data on individual

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1 'Turnkey' technology - This refers to the import of hardware, technical experience and capacity utilization patterns lock, stock and barrel from advanced industrial countries by developing countries.

2 'Least-cost' technology (as defined by Bhat and Pandergast) in any particular set of circumstances is the combination of those alternative techniques at each stage of the process, which are themselves least cost in that set of circumstances.

activities within a plant to provide the basis for more rigorous micro-economic analysis.

Howard Pack (1974), in examining the relation between choice of technique and employment in the textile industry used data on activities at the sub-process level to trace out production isoquants (linear programming isoquants), with three, four or five techniques.

His fundamental question was whether older techniques available in developed countries might allow more efficient substitution (by comparison with newer techniques) of labour for capital, and, if so, whether such substitution should prove economically efficient for developing countries. Pack looked at the kinds of machines (and numbers of each), power requirements, material wastage, space use and labour requirements. He could then trace out the substitution possibilities among the inputs and examine the economic efficiency of such substitution at a variety of relative factor prices.

Pack assessed the efficiency of specific pieces of equipment in producing specific products and examined the ways in which labour may be substituted for capital. One drawback to his analysis, however, is that he failed to consider the life of equipment, and so he assumed that the old equipment had the same life as the new equipment and so purchase price and availability were all that mattered to him.

Pickett and Robson (1977) in their study of technology and employment in the production of cotton cloth, went a step further and actually computed the elasticity of substitution of capital for labour. They chose four stages in the production of cotton cloth, which could be considered as independent of each other. They then identified nine different technologies from the combinations available, that could, in principle, be used in the making of cotton cloth. They were able to plot the points in relation to capital and labour use for some eighty-one technologies capable of producing a given quantity of cotton cloth (20 million square metres) and so, an isoquant could be drawn and the inefficient technologies eliminated.

The authors included in capital cost not only machinery but also buildings, installation charges and working capital. They also took account of wage differentials between skilled and unskilled labour by designating labour in equivalent units. They also found it convenient to relate technology to a constant value added associated with a given physical output rather than to the output directly.

Their more extensive and formal use of engineering data allowed them to draw some fairly novel conclusions. Assuming that technological choice by firms is made either on the basis of the rate of profit or the absolute surplus earned, they compared profit, surplus and numbers employed in relation to the main technologies identified, under different country conditions, and turned up some interesting results. They found that, using both criteria for technological choice, Latin America and Africa were more profitable locations for the production of cotton cloth than Western Europe and that, again on both criteria, there was much more variation in employment across technologies in each of the developing regions than there was in profitability. This second finding meant that one technology which would increase employment by, for example, one hundred and seventy-three percent over another, would still provide eighty four percent (in a particular case) of the surplus associated with the second technology.

This study therefore, is illustrative of the way in which engineering data might be used for wider applicability. In this case, the authors were concerned with whether the alternative technologies were profitable. There is, however, a great need for examination not only of profitability and employment but of minimizing the use of inputs in the production of a given output (i.e. making the most out of what is available).

McBain's (1970) study of footwear manufacture was among the major studies using engineering data to relate inputs to outputs in a productive enterprise. Like Pickett and Robson (1977), he divided the production process into work stages, which were supposed to be relatively independent, using material movements as the break points. As with most of the other studies he was interested in employment and hence, in factor substitutability.

Alternative technologies were appraised on the criteria of private and social net present value. Employing a particular set of factor prices, it was possible to establish which of the alternative modules[1] at each work-station[2] was

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1 A module refers to a set of techniques which comprise a sub-process technology involved at a particular work-station (see 9 below).

2 Work-station - a point where the technology belonging to a particular activity or stage in the process is carried out.

preferable. Given the stated independence of the production stages considered, the least cost combination of modules for all the work-stations could be summed. The cash flows for the complete project which incorporated the least cost combination of modules for a particular set of prices could then be obtained.

Again, there was the tendency to assume independence of the individual sub-processes. The study does, however, provide some fresh insights. Sensitivity and risk analysis are applied to the results. The study was one of the first to make comparisons in the performance of a large number of synthetic technologies.[1]

Two other studies, one by Uhlig and McBain (1977) on Nut and Bolt manufacture, and another by Forsyth (1977) on Sugar manufacture, both recognised the need to use sub-process engineering information and to build up to plant level using several different synthetic technologies to allow for wider applicability of the results of the study.

These authors were among those associated with the University of Strathclyde's David Livingstone Institute and were involved in the project on Technological choice in developing countries.

The study by Uhlig and McBain was the first in the Strathclyde series to deal with batch production. They performed a sub-process analysis using work stations to demonstrate that savings could be made by selectively drawing on different technologies to manufacture the different batches included in a product mix.

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1 Synthetic technologies - combinations of sub-processes which form technically feasible overall technologies which may or may not exist in any existing plant.

Uhlig and McBain make an important contribution by their treatment of a product mix and their concern for the way in which the chosen product mix affects the least cost technology combination. This analysis of product mix, however, is useful only in relation to batch type processes.

They also plainly point out the limitation of analysis on a task or subprocess level only. They are aware that what is done at one stage in the processing chain may closely circumscribe the tasks that are to be performed at aubsequent stages, or affect the costs downstream. The task level alone also overlooks the economies which can be derived from the use of a single indivisible machine for more than one task. In addition, task level analysis neglects to consider the importance of 'massed resources'[1].

Forsyth's (1977) study of sugar manufacture, recognises and tries to avoid many of the limitations of the other similar studies on technological choice. Because of the partial nature of many of the other analyses, the result has been, little hard evidence on what constitutes the appropriate technology in any given set of circumstances.

Forsyth therefore made an extensive empirical investigation into the fundamental economic and engineering aspects of sugar production. He considered the technological alternatives at the sub-process level and derived a large number of feasible combinations of the sub-process variants. He

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1 The term 'massed resources' resources refers to the operation of the law of large numbers. For example a firm with several identical machines will have to stock proportionately fewer spare parts than a plant with only one. (See Pratten and Dean (1965), The Economies of Large-Scale Production in British Industry: An Introductory Study, Cambridge Univ. Press, p. 18).

ended up with a fully costed range of alternative technologies, and for each one the characteristics of inputs and outputs, and the technical interrelations between sub-processes were known.

He developed a fully articulated set of life-span cost and revenue profiles, one for each alternative composite production process. A Discounted Cash Flow (DFC) analysis was carried out and the net Present Values were computed using observed market prices and then using shadow prices (using the Little and Mirlees technique). Sugar production was divided into some thirteen principal sub-stations and the alternatives were examined at each stage, as usual. A sensitivity analysis was also carried out.

However, Forsyth chose to compare the technologies at only four different levels of scale - 5,000 tons per annum (tpa), 25,000 tpa, 10,000 tpa, and 100,000 tpa. Using the results from his analysis of these synthetic technologies, he was able to come up with a conslusion different from those generally arrived at by persons studying technological alternatives for developing countries. He found that:

> "..... Contrary to recent suggestions in the literature, capital intensive technology is shown to be clearly superior at all but the smallest level of scale, and unit costs are found to fall sharply as output rises"[1].

This thesis is an attempt to move to a more rigorous analysis of the alternatives available by going back to engineering fundamentals to derive a relation between

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1 Forsyth (1977, p. 189).

physical inputs and outputs (the real production function) at a very micro level (the individual food engineering operations or groups of operations) and then to bring the analysis to the plant level without ignoring the inter-relationships within the plant.

The study uses the technique of Dynamic Programming[1] to assist with the process of plant level optimization which avoids the obvious problems associated with assuming the sub-processes technologies to be completely independent. The relationship between inputs and outputs (in keeping with the use of the production function concept) can now be identified at the plant level by a technique which, by the use of engineering based data, allows the plant level alternatives to be identified in a less restricted set of circumstances.

The study involves a reasonable knowledge of engineering principles and also some familiarity with the plant technology itself. In making the dairy industry the focus of the study, an in-depth study of dairy technology had to be made. The following chapter gives an overview of manufacturing technology for a wide range of dairy products, to provide an introduction to the type of processes that are being dealt with in the later analysis of the relations between inputs and outputs in a plant designed for the processing of pasteurized milk.

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1 This optimization technique is discussed in Chapter 4.

CHAPTER 3

TECHNOLOGICAL OVERVIEW OF THE DAIRY PROCESSING INDUSTRY

This chapter is designed to provide some preliminary insights into the nature of the technology used in the production of a wide range of dairy products, and how plant technology may be disaggregated to facilitate the analysis of technological choice. This overview lays the foundation for the more in-depth study of the relationships between inputs and outputs in a pasteurized milk plant which is the focus of this study.

The first section is a survey of the major types of processed dairy products with a brief and somewhat cursory look at the methods used in the processing of each product. The survey covers the fluid or market milk products (pasteurized, sterilized milk, etc.) and the "manufactured" milk products (butter, cheese, etc.), including some of the more traditional milk products (e.g. khoa).

In the second section attention is directed to the disaggregation of plant technology in fluid milk plants such as those producing the pasteurized market product. A basis for delimiting the boundaries of the sub-processes (or stages) of production - a concept central to the analytical methods being applied in this thesis - is suggested.

Once the basis has been established, the technological alternatives at each sub-process can be identified. This is done in the third section of this chapter.

3.1 Dairy Products and Processing Technology

The Dairy Products Industry lends itself particularly well to an engineering study of this nature because many of the transformations involved in the processing of the products are of a chemical nature. With chemical transformations, the "design laws" incorporated in the equipment used are fairly readily accessible to serve the purpose of assessing the physical relationship between inputs and putputs. This, of course, is also true of most of the other food processing industries.

In general, the technology may be described as "equipment based" in that the processing activities in the plant revolve around various pieces of equipment appropriate for carrying out the particular operation required on the input "commodity"[1] involved at that stage. These characteristics of the technology facilitate the use of the particular analytical methods being employed in this thesis and this becomes more evident in later chapters. Their absence does not in anyway preclude the use of these methods, it only renders the task more difficult as hard data become more elusive.

Before making a detailed study of pasteurization technology, a brief survey of dairy products will be made, highlighting the more salient characteristics of the products, the processing techniques used and other features relevant to the study. The product field is then narrowed to a single type of product in order to avoid the vagueness and

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1 The term "commodities" is used to describe the outputs of material along the production stream.

superficiality which would tend to be present in a broader-based study. References are made to the applicability of the methods discussed for that single product to the other products not being considered, where appropriate.

Dairy products may be classified broadly into two major classes, namely i) Fluid or Market milk products and ii) "Manufactured" milk products.

Processing facilities are designed to produce either fluid-milk products or one of the manufactured products. Products considered to be in the fluid milk category include whole milk (pasteurized, sterilized, homogenized), partially or fully skimmed milk (low fat); chocolate milk, cream and cultured buttermilk. There are also some fluid milk products which meet certain dietary or health requirements. These include Multi-vitamin mineral milk, low sodium milk and immune milk.

Manufactured milk products include most of the non-beverage products, such as ice-cream and frozen desserts, condensed, evaporated and dry milks, cheese and butter.

The processing of dairy foods involves some or all of the following operations: Fluid-transport operations; Heat-transfer operations; Centrifugal operations; Fermentation; Vacuum-Steam treatment; Hydrocoleoid stabilization; Emulsification; Flavouring; Ion-exchange treatment; Churning; Freezing; Drying; Condensing; Nutrient fortification; Chemical stabilization.

The two major classes of dairy products are now examined more closely to give an appreciation of the principal characteristics of dairy products and of the technology involved in their processing, before launching into an in-depth technological analysis of a single product.

3.1.1 Fluid or market milk products

The most widely known of the market milk products is pasteurized milk, and this product has been selected to illustrate the application of the analytical techniques used in this thesis. Thus only a brief sketch of the product and its technology is provided in this section as an introduction to the overview of the fluid products and their technology. The full list to be considered is:

a) Pasteurized milk
b) Sterilized milk
c) Homogenized milk
d) Skim milk (liquid) and cream
e) Buttermilk and soft curd milk
f) Special milk products
g) Recombined and Toned Milks.

a) Pasteurized milk

The pasteurization of raw milk from the farm is done primarily to improve the health standards of the milk and expand its life, allowing the product to reach a much wider market and provide fewer health risks than the raw product would. The process is designed to remove all the pathogenic organisms found in the raw milk and so, in most countries, this form of processing is considered essential to the maintenance of proper health standards. Many other milk products also receive this treatment.

Raw milk from the farm contains many harmful bacteria and may be further contaminated by dirty and infected milking pails and cans. Where milking machines are used, the complicated construction of these machines makes cleaning difficult and so these machines may be an additional source of bacterial contamination. Where cows are themselves unhealthy or diseased and where the udders are not frequently washed, the milk direct from the animal may be contaminated. Many diseases are transmitted through contaminated milk. These include Tuberculosis, Typhoid fever, Diptheria, Scarlet fever, Septic sore throat, Brucellosis and various intestinal disturbances.

Pasteurization, therefore, is essentially a heat treatment process which is one hundred percent effective in destroying the disease causing bacteria, and most of the other bacteria. Approximately 90-95 percent of all bacteria are destroyed. All yeasts and moulds generally are killed by pasteurization. It may be noted that the pasteurization procedure stops short of destroying all organisms in the milk. When this is done, the process becomes known as sterilization, and this type of fluid milk product is dealt with below.

The pasteurization process is not altogether a simple one. It requires strict control of the temperature to which the milk is heated combined with the length of time during which the milk is held at that temperature. If the milk is held at too low a temperature for too short a time then sufficient of the pathogenic organisms will not be destroyed, whereas, if the temperature is too high and held for too long, then a "cooked" flavour is imparted to the milk. For these reasons milk processing countries usually enact legislation which specifies the precise time-temperature combinations required for the parteurization process to be acceptable.

The time-temperature combination specified by the U.S. Food and Drug Administration is as follows[2]:

Temperature		Time
^{o}Centigrade	^{o}Fahrenheit	
62.8	145	30 minutes
71.7	161	15 seconds
88.4	191	0.1 second
95.6	204	0.05 "
100.0	212	0.01 "

The law also stipulates that if the fat content of the dairy ingredient is 10 percent or more or if it contains added sweeteners, the specified temperatures must be increased by 2.8^{o} Centigrade (5^{o}F) in the case of the first two combinations listed above.

Pasteurization at a temperature above 71.7^{o} Centigrade (161^{o}F) is known as High-Temperature-Short-Time (HTST) pasteurization (also called Flash pasteurization). The lowest temperature and longest holding time (62.8^{o}C for 30 minutes) is the usual combination used in the batch-holding pasteurization process. These two processes are at the extremes of pasteurization technology - the HTST process requires more advanced specialized equipment for a carefully

2 See Lampert, L.M. (1975, p. 169).

controlled higher-speed continuous flow operation whereas the slower batch process is done in vats.

After pasteurization the milk must be cooled immediately to 7.2° Centigrade (45°F) or less in order to retard the growth of surviving organisms and needs to be protected from contamination.

The pasteurized product for the fluid milk market may also be homogenized (discussed under (c)). This is optional and depends on the preferences of the market. The product characteristics are changed as the homogenization process breaks up the fat in the milk and prevents the formation of the line of cream which rises to the top of milk when it is left standing. In some countries, notably the United Kingdom, the consumers are reputed to have a preference for a product with a "cream line" and so pasteurized market milk products are usually left unhomogenized.

The pasteurization process destroys some of the nutrients in the milk, however. It is estimated that about 10-20 percent of the thiamine originally present in the milk is destroyed by pasteurization. However, this is reported to drop to only about three percent when the HTST process is used.

Since this product has been selected as the principal dairy product to be analysed thoroughly in this thesis, its characteristics and its technology will be scrutinized subsequently much more closely.

b) Sterilized milk

There are several different processing techniques used for producing the sterilized products. The major characterist of the sterilized milk products, however, is that the milk has been heated to a temperature sufficiently high to destroy all living organisms in the milk. The product must also be free from post-sterilization contamination. The milk may be sterilized after being placed in the container (can or bottle), or it may first be sterilized and then aseptically packaged in cans or cartons. The product then requires no refrigeration until it is opened.

Unlike the pasteurized product, the sterilized product usually has to undergo the process of homogenization (discussed under (c)) of 5,000-8,000 pounds pressure to minimize the development of a chalky flavour in the milk. With pasteurized milk homogenization is optional, as mentioned previously.

Because of the severity of the heat treatment involved, there is some loss in the thiamine and Vitamin B_2 content of the milk which is greater than that lost in the pasteurization process. Lampert (1975) estimates the thiamine loss to be as high as 40 percent.

In the first approach to producing a sterilized product for the fluid milk market, the unsterile product is bottled or canned and then sterilized in the container.

In the case of in-bottle sterilization, the unsterile homogenized product is filled into narrow neck bottles with 2¼ inch head space, and capped with airtight crown closures. In a batch process, the filled bottles are placed in a large pressure oven or autoclave in crates. The temperature is raised to 105^{o} - 110^{o}C ($220-230^{o}$F) and held for twenty to forty minutes. The crates are removed and the bottles allowed to cool naturally.

In the typical continuous in-bottle process, the filled and capped bottles are placed in cradles which move on a continuous conveyor system through a series of tanks containing water of increasing temperature. The speed is regulated so that sterilization is effected when the bottles reach the end of the line.

In the case of in-can sterilization there is also a choice of batch or continuous systems. In the batch system, there is a container or metal basket which revolves in a steam-tight container, similar to a large pressure cooker. The milk is heated gradually to 118^{o}-121^{o}C (245^{o}-250^{o}F) at about 2-3^{o}C per minute. It is held for fifteen minutes. The sterilizer is then filled with cold water and the cans are cooled quickly to about 32^{o}C (90^{o}F).

In the typical in-can sterilization system, the unsterile product is filled and sealed into cans which then pass into the sterilizer line system. The cans pass into the preheater, then through the leaky can detector, through to the pressure sterilizer. They then go through a transfer valve under pressure to the pressure cooler, and finally to the second leak detector.

In the second approach to producing sterilized milk, the milk is first sterilized and then packaged. How these methods have evolved over the years is described below.

In the pre-1940 method the Heat-Cool-Fill (HCF) method was used in the U.S.A. for sterilized Chocolate Milk in cans. The cans and covers were sterilized with steam and then passed through rotary valves into a closed chamber where they were filled with the cold, previously sterilized, product.

After 1940, glass containers were used with a method known as the AVOSET process. Sterilization was by the direct injection of steam, with evaporative cooling. Glass containers and their closures were sterilized in a continuous hot air sterilizer which discharged them into a filling room. The air entering the room was sterilized before entry and germicidal ultra-violet lamps were used in the room to prevent contamination during the filling operation.

More recently, the Ultra-High-Temperature (UHT) method - a short-time higher speed sterilization process - was developed and this is combined with aseptic packaging. The DOLE Aseptic Canning system is typical of the can filling techniques for UHT milk. This process is often used for longer-life products which may require storage for several months and is generally used with the manufactured milk products such as evaporated (condensed) milk discussed in Section 3.1.2. It is also used for whipping cream, coffee cream and ice cream mix.

In this canning system, the filling and closing machine is sterilized with superheated steam at almost atmospheric pressure. The empty cans are carried on a conveyor through a tunnel where they are sterilized with superheated steam up to 288° Centigrade (550°F). The cans themselves reach up to 425°F, just below the melting point of tin. The can covers are done similarly on a separate line. These sterilized cans pass under the filler and are filled with the cold milk which has been cooled in the regenerative part of the UHT sterilizing system (described below).

Much of the every day market fluid milk is packaged aseptically in cartons, with the Tetra-pak filling system being the best known. This system is used with UHT sterilized milk.

There are several types of equipment in which the UHT process is carried out. In all of them the raw milk is preheated, raised to the Ultra-high temperature of 150° Centigrade (302°F), homogenized (described under c)) and coded regeneratively[3] in one continuous system. The milk is then ready for aseptic packaging.

The many different makes of equipment for UHT processing may be classed into two basic types - direct heating and indirect heating. In the direct heating equipment, the steam for heating is injected directly into the milk to be sterilized, whereas in the indirect heating system, the heating medium (steam or water) does not come into contact with the product being heated.

The range of direct heating systems includes: The Alfa-Laval UTIS (vacu-therm instant sterilizer) compact; the APU Uperizer; the Cherry-Burrel sterilizer, and the Paasch and Silkeborg Polarisator. The indirect heating

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3 In a regenerative heat exchange system, the heated product leaving (entering) the system heats the cold product entering (leaving) the system and is in turn cooled by it.

systems include: the Ahlborn Indirect Heating Sterilizer, the Alfa-Laval Indirect Heating Sterilizer; the APU Ultramatic Sterilizer; the Cherry-Burrell Indirect Heating Sterilizer; the Sordi Steriplate Sterilizer (compact); and the Stork Stendeal Sterilizer.

The actual choice of equipment rests on the demands of the final product. A UNIDO (1969) study compared the annual unit costs of a direct and an indirect heating system by the same manufacturer and found the cost of the direct heating system to be higher. This was mainly because of the higher capital cost and greater use of steam and water.

In general the capacity of the equipment is not very flexible. Those systems described above as compact, are assembled in the factory of manufacture and shipped as a compact unit. Mounting in the dairy only involves the connection of steam, electricity, water and air. The other types of equipment are floor mounted, and so are more costly to install. The equipment is usually of the Cleaned-in-place (CIP) type[4].

In one of the most popular types of aseptic packaging in paper cartons, a filling system, developed in Sweden, forms, fills and seals the carton. The system utilizes a strip of polyethylene coated paper which comes in rolls. Before filling, the paper is passed through a sterilizing bath, the machine then forms it into a tube and it is heat sealed longitudinally at a temperature of about 400^{o}F. The

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4 Cleaned-in-place equipment does not have to be dismantled for cleaning but is instead fitted with pipes and valves so that water and cleaning agents may be circulated through it.

UHT sterilized milk enters the tube from above through a stainless steel pipe as the container is formed (literally) around the milk. The tube is sealed transversely under two tons of pressure. The containers are filled in a continuous chain and are sheared apart into individual units and packed automatically into the shipping carton.

The costs for aseptic filling are high, particularly when added to the cost of processing by the direct heating method. On the processing side alone, these sterilizing costs are estimated by UNIDO (1969) to be 25-30 percent higher than pasteurization costs.

It may be noted, however, that when non-processing costs (i.e. distribution, storage, etc.) are taken into account the sterilized product may become economically justifiable because of its cheaper distribution and storage costs (no refrigeration necessary), reduced product losses (less perishable) and greater convenience for consumers particularly in areas without electricity for refrigeration and in areas remote from the processing plant.

It is clear, therefore, that the choice of processing technology is only <u>one</u> dimension of the selection decision for having a product that meets the particular needs of a country or any identifiable political or economic entity. The choice of the product itself must also be taken into account and ex-factory costs (social and/or private) must be evaluated.

However, for a full comparison to be made, an in-depth analysis of the technological alternatives at the plant level must be made, so that the least-cost technologies can be established, for the respective products that are considered to be substitutes in meeting a certain well-defined need. It is this dimension of the problem that this thesis seeks to resolve by using a single product as an example and demonstrating how the most appropriate in-plant methods nay be determined.

Once these in-plant costs for the respective products are known, other outside costs and benefits (however measured) may be computed for the individual products to give a much broader and more complete basis for comparison.

c) Homogenized milk

The United States Public Health Service Milk code[5] defines homogenized milk as

"... milk which has been treated to ensure breaking of the fat globules to such an extent that, after forty-eight hours of quiescent storage at 45°F, no visible cream separation occurs in the milk, and the fat percentage on the top 100 millilitres of milk in a quart, or of proportionate volumes in containers of other sizes, does not differ by more than ten percent from the fat percentage of the remaining milk as determined after through mixing."

Unlike pasteurization, this process is not carried out for health reasons. It changes the characteristics of the final product by preventing the formation of the cream line at the top of the milk and so is primarily for cosmetic reasons to cater to the tastes and preferences of the consumer.

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5 See Lampert (1975, p. 192).

The market milk product sold as homogenized milk would therefore also have been pasteurized. In some countries the homogenization process is considered non-essential.

The homogenizer itself was invented in France about 1902 and patented in the U.S.A. in 1904. It was not until the 1930's that the homogenized product became popular in the U.S.A.

Milk is homogenized by pumping it under high pressure through the very small opening between a valve and its seat, or between the narrow spaces of a series of discs pressed against one another by means of a heavy spiral. The homogenizer is essentially a high pressure pump of the positive displacement type. Pressures of 1,700-3,000 pounds per square inch are often sufficient to prevent the formation of cream on the milk.

Some of the advantages which are obtained from adding the homogenization process include: richer flavour and colour; more uniformly distributed fat in the product; greater digestability; and superior results in cooling.

However, there are certain disadvantages which must be weighed against the above advantages and these include increased production costs, the possibility of sediment in the bottom of the packaged product; more rapid flavour deterioration; the equipment being an additional source of possible contamination of the milk; and the problems in using the returned homogenized milk as the fat cannot easily be used for making butter. Sterilized milk and some other milk products require homogenization for various reasons.

d) Skim milk and cream

Skim milk and cream may be considered joint products of the same process. Skim milk is a low or non-fat milk and is the portion of the milk that remains after part or all of the cream has been removed.

Cream may be separated from the skim in either of two methods. In the first method, the milk is allowed to stand, and the cream is the portion of the milk, rich in milk fat, that rises to the top and can then be removed. Alternatively, a piece of equipment known as a cream separator may be used. The separator is a bowl which rotates at 3,000 to 20,000 revolutions per minute and consists of a series of conical discs separated from each other by projections upon their surface. The separation takes place using centrifugal force, with the warm milk (32°C) entering through holes near the centre of the discs and the cream, which is lighter than the skim, being driven by the force towards the centre of the bowl while the skim is driven outwards.

Skim milk contains all the nutrients of milk with the exception of the fat and the vitamins associated with the fat. These vitamins are often added when the milk is supplied for human consumption. Not all the skim milk is marketed as liquid milk. The product may also be used for the manufacture of cheese or chocolate drink or made into condensed or dried skim milk.

Similarly, not all cream is sold as market cream. Cream is also used in the manufacture of butter and ice-cream.

The market cream appears in several different forms and with various proportions of milk fat. Light table cream contains 18-30 percent fat, with light whipping cream this rises to 30-36 percent while the heavy whipping or pastry cream reaches 36 percent milk fat.

e) Buttermilk and soft curd milk

Buttermilk and soft curd milk are both liquid products processed for easy digestion. Milk with a hard curd, which is higher in casein[6] is more difficult to digest and so the softer curd is especially preferred for children. In general cows' milk has a harder curd (higher curd tension) than human milk, and even when boiled it is still more difficult to digest.

Buttermilk has a curd tension that is practically zero. Genuine buttermilk is a by-product of the buttermaking process. It is the liquid remaining after the fat is removed from milk or cream while churning butter. When buttermilk is made from sweet cream or milk it is not materially different from skim milk. It may also be made from sour or fermented milk or cream, and then lactic acid is present and there is less sugar in the buttermilk.

The buttermilk is also used in the manufacture of ice cream mix, bakery products, and animal feed. Lampert (1975) estimates that pasteurization reduces the curd tension by about 20 percent and if homogenization is done as well, it is estimated that curd tension reduction amounts to about 60 percent.

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6 Casein is the main protein of milk which is obtained from the skim milk by acidifying the milk.

f) Special market milk products

Some market milk products are processed specially for health reasons and to assist in the medical treatment of some diseases, or to correct certain dietary deficiencies. In the U.S.A., low sodium milk, immune milk and multi-vitamin mineral milk are some of these products.

Low sodium milk is processed to assist in the treatment of diseases accompanied by high blood pressure or oedema (swelling). It is a process involving ion-exchange and designed to reduce the sodium content of the milk from the 56 mg. per 100 ml. of milk to a limit of 5 mg.

In one process the milk is prepared by an ion-exchange procedure using a phenosulforic acid type of resin which contains both potassium and calcium in such concentration that the minimum of calcium is removed from the milk but the sodium is substituted by potassium.

In another process the milk is passed through an ion-exchange resin in the potassium form and then through calcium - hydrogen resins.

The production of immune milk starts on the farm where an antigen infused in the mammary gland to make it produce a particular antibody. This antibody is absorbed from the gastrointestinal tract into the blood when the milk is consumed. This was designed as a treatment for cases of Rheumatoid Arthritis but is not generally favoured by physicians. In the U.S.A., this milk is no longer prepared.

Multi-vitamin mineral milk is also, like immune milk, not particularly favoured and is illegal in many parts of the U.S.A. In this process, the milk product is fortified with vitamins and minerals.

Some milk products are specially flavoured for the market. Chocolate flavoured milk is perhaps the oldest of them all. Several other flavours are now available in Western markets. Where the product has in it less than the legally required amount of milk fat, the product has to be labelled "drink" instead of "milk". In the case of chocolate milk the dietary effect may be adverse in that excessive consumption of chocolate tends to lower the retention of dietary calcium and phosphorus.

g) Recombined and toned milk

The processing of toned and recombined milk is usually done in countries where the supply of fresh liquid raw milk from the local dairy farms is inadequate. The principal characteristic of the processes involved is the use of dried milk powder which is reconstituted to augment the supply of processed milk in the market.

In the case of toned milk, water and non-fat dry milk are added to the locally produced milk, lowering the overall milk-fat content of the milk. The blend is filtered, pasteurized, homogenized and then bottled. Refrigeration for twelve hours is considered desirable as it is said to improve the product. This type of milk was produced in India after the Second World War. Warner (1976) also identifies double-toned milk with half of the milk content of toned milk (1.5% in India).

In a full recombining plant, reconstituted whole milk can be made by combining dry skim milk powder with anhydrous milk fat[7]. After being mixed, blended and agitated, the product is pasteurized and is also usually homogenized and processed in much the same way as fresh milk is processed for the liquid milk market. The reconstituted product is reputed to have the same qualities and consistency as fresh whole milk.

There are certain important advantages for non-dairying countries and remote areas for producing recombined and toned milk. These advantages stem primarily from the good keeping qualities of the principal raw materials - dried skim milk powder and anhydrous milk fat. Dried skim milk prepared by the spray drying process[8] is well known for its keeping qualities and easy reconstitution. A USAID (1962) study indicates that anhydrous milk fat is a product which can be stored in airtight containers without refrigeration for two to three months at temperatures below 38°C (100°F).

A recombining plant may make other products for the liquid milk market including: liquid skim milk; cream; buttermilk; chocolate and fruit milk drinks. The recombined product may also be used in other manufactured milk products such as: Ice cream; cottage cheese; yogurt and in fermented milk drinks.

3.1.2. Manufactured Milk Products

The list of manufactured milk products ranges from the well known factory produced items such as concentrated and dried milks to the more traditional cottage products known

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7 Anhydrous milk fat, sometimes called butter oil, contains 99.8 percent butter fat. It is a product which has had most of the moisture removed.

8 See Section 3.1.2(a).

only within certain localities or in individual countries. Some of the more well known products such as butter and cheese have their origins way back in ancient cultures with special local varieties and processing methods ranging from traditional cottage types to the more advanced large plant methods.

The full list of manufacrured milk products to be considered is:

a) Concentrated milk products

b) Dried milk products

c) Ice Cream

d) Butter

e) Cheese

f) Cultured and fermented milk products

g) Traditional local milk products.

a) <u>Concentrated milk products</u>

Concentrated milk products come in very many different varieties. It is estimated by the U.S. Agency for International Development that in the U.S.A. there are at least fifteen different condensed products which may be marketed in an infinite number of concentrations for special purposes[9].

The main bases for classifying the concentrated products are a) whether the milk is skim or whole and b) whether the milk is sweetened or unsweetened[10]. Where the milk to be condensed is skim milk then the cream separation process is carried out on the raw whole milk (see Section 3.1.1a),

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9 See U.S.A.I.D. (1965).

10 Unsweetened condensed milk.

before the concentrating of the milk is done. For the unsweetened condensed (evaporated) milk the preservation is by heat sterilization treatment whereas the sweetened condensed milk is preserved with sugar.

The milk to be concentrated is always standardized to ensure that the product has the desired ratio of solids to fat. Skim milk of cream may be added when and if necessary for the type of product being produced. A piece of equipment known as a standardizer may be used. It operates on the principle of centrifugal force in much the same way as the cream separator (see Section 3.1.1a). A single piece of equipment may be used as separator and standardizer. The equipment may be adjustable to give different fat contents. Additionally the job of clarifying the milk (removing dirt, leucocytes, bacteria, etc.) may be carried out using a combined clarifier-separator-standardizer.

For unsweetened condensed milk (skim or whole) the milk is concentrated to a ratio of approximately 2.25 pounds of liquid milk to one pound of concentrated milk. This concentrating is usually done under vacuum to reduce the boiling point. The choice of concentration at atmospheric pressure exists, but this means that evaporation must take place at a temperature slightly above the boiling point of 100° Centigrade (212°F). This is generally considered undesirable particularly because it gives the product a "cooked" flavour. Thus the alternative "vacuum pan" technology is favoured. By concentrating under vacuum, the evaporating temperature can be reduced to 43-57°Centigrade (110°-135°F).

Further reductions in temperature may be obtained through the use of the more advanced technology involved in the multiple effect evaporators where evaporation is done in several stages.

The multiple effect evaporators have important consequences for the quantity of steam used. Steam use diminishes as the effects increase though less than proportionately. To evaporate one pound of water a single effect evaporator uses 1.2 pounds of steam. This reduces to 0.6 pounds of steam in a double effect evaporator, and to 0.4 and 0.3 pounds respectively for the triple and quadruple effect evaporators[11].

A low temperature concentrator is another alternative. This equipment uses a refrigeration cycle which allows extreme low temperature evaporation. No cooling water is required for condensing the liquid and no source of heat is required. It is only electricity that is needed to operate the compressors.

The unsweetened evaporated milk is homogenized and bottled or canned after which it is sterilized using procedures similar to those described under "in-bottle" and "in-can" sterilization (see Section 3.1.1b).

Sterilized, canned evaporated milk will keep indefinitely, and has a softer curd than that of most raw or pasteurized milk, thus making it easier to digest and hence more suitable for infants.

Some of the nutritive value of milk is lost in the processing as the heat treatment destroys between 20-33 per cent of the thiamine. About 50 percent of the ascorbic acid

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11 See Farrall (1963, p. 404).

(vitamin C) in the original milk is also lost. The milk, however, is a good source of vitamin A.

For the sweetened condensed product, the milk is heat treated to inactivate enzymes (82-94°C) and remove pathogenic organisms and then the preserving syrup is added, with the sugar forming about a sixty-three percent solution with the water in the finished product. The mixture is evaporated similarly to the unsweetened product with 2.5 pounds of the mixture being evaporated down to one pound.

The sweetened condensed milk must be cooled quickly and agitated to prevent crystallization. It is then canned and does not require refrigeration.

Sweetened condensed cream and condensed skim milk products may also be made.

b) Dried milk products

The processing of dried milk products is a stage further on from that of the manufacture of condensed milk products. After evaporation, the concentrated product is fed to various types of driers. The choice of drying technology determines the characteristics of the final dried product.

Basically there is a choice between roller (drum) drying and spray drying. Roller drying may be done at atmospheric pressure or under vacuum. As with the concentrating process (discussed in (a) above) the vacuum process involves lower temperatures, which in this case means that the product (dried milk) is more soluble than with the high heat atmospheric process. The rollers (or drums), which drip into the condensed milk, are heated internally by hot water or steam and when used at atmospheric pressure require a heat of 95°-150° Centigrade (200-300°F), whereas the vacuum process requires a temperature lower than 100° Centigrade.

Skim milk powder produced by the roller (or drum) method is not generally used for human consumption. Even the more soluble low heat powder is difficult to reconstitute in the home. This product is therefore often used for animal feed.

The spray drying process is much more popular for dried milk intended for human consumption. Lampert (1975) estimates that approximately 80 percent of all dry non-fat (skim) milk and nearly all whole dry milk is made by the spray drying process.

After being concentrated to between 40-45 percent total solids, the milk is forced in a fine spray through a stream of heated air in the spray drier. Heated air at 176°C (350°F) is generally used for skim milk powder.

The spray drying equipment has a higher capital cost and is more intricate than the roller driers. However, the output is a coarser powder which is more soluble and has a more natural flavour.

More recently, a more advanced technology has been developed for producing a dried milk with high solubility for instant reconstitution in the home. The instantizing process produces a powder in which the particles are clustered or agglomerated, so that they break up when water is added, allowing each particle of powder to disperse instantly and dissolve.

A choice exists between one-stage and two-stage instantizing. Some systems take the previously spray dried milk and rewet and redry it to make the more soluble product, but in the "single pass" process the liquid non-fat milk is made into "instant" powder in a single stage.

It may be noted that the processes discussed so far are mainly suitable for non-fat (skim) milk. Dry whole milk does not keep very well and moisture induces a stale flavour in the product. A process known as foam drying is generally used for producing whole dried milk powder. The process involves the use of Nitrogen or Carbon Dioxide gas to create a foam concentrate which is then dried in a drying chamber.

Cream may also be dried using a spray drying process. It can be stored for several months at room temperature.

c) <u>Ice cream</u>

Ice cream is essentially a blend of cream, milk, sugar and flavouring. Dried products, dried skim and anhydrous milk (fat) may be recombined as for the production of whole milk (see Section 3.1.1g). When milk and cream are used, condensed or dry non-fat solids have to be added to increase the proportion of solids - not fat in the mixture to meet the requirements for commercial ice cream.

In addition, sugar, stabilizer, an emulsifier, flavouring or prepared ice cream mix must be included in the mixture, and the mix may be prepared in a pasteurizer used for batch processing or HTST pasteurizer - (see Section 3.1.1.a) - may be used. The product is homogenized and cooled to around freezing point and packaged. It is then hardened and stored.

An alternative technology to the batch or individually controlled stage method is the continuous flow technology with a high degree of instrumentation - a process which may be operated by remote control by one person.

It may be noted that the colume of ice cream is determined by the extent of the overrun, which is the increase in volume that is obtained from whipping air into the milk during the freezing process. In some ice creams the overrun may reach 150 percent.

The freezing of the ice cream may be done either by batch or by continuous methods with the continuous method being much faster (22 secs. vs. 7-8 mins.), and allowing greater control of the overrun. The air that provides the overrun is, in the continuous process, pumped in with the mix.

The ice cream, after freezing and packaging, has to be hardened with the use of very low temperatures (-29° to $-45^{\circ}C$ (-20° to $-50^{\circ}F$)). A hardening room may be used or the product may be conveyed through a hardening tunnel where the product is cooled quickly by a blast of high velocity cold air.

Ice cream is high in calories with 150 calories per 100 grams where the product contains 4.5 percent fat and 33 percent solids. However diabetic ice cream may be made using a sugar substitute. Additionally, a dietetic low sodium ice cream may be made using spray dried low-sodium milk powder (see Section 3.1.1.f).

d) Butter

Butter making is a very ancient craft which was carried out on a household or cottage scale in traditional societies, and, in Indian village society, the amount of butter a man produced was supposed to give some indication of his wealth. Nutritionally, butter is a good source of vitamin A.

Although buttermaking is still done on a cottage scale, there are more advanced larger scale processes which are used in buttermaking plants for the mass marketing of butter.

The manufacture of butter is based on cream. When the cream is separated from the skim milk in the separation process (discussed in Section 3.1.1.(d)) the cream may be diverted to the buttermaking process.

The cream, if sour, must first be neutralized by the addition of an alkaline compound. It is usually standardized to achieve a desired fat content (usually 30-33% fat) and then pasteurized using batch or continuous pasteurization technology. A special vacuum process may be used to remove undesirable odours and flavours. It is then cooled and allowed to "ripen"[12] before it is churned.

The churning of the butter is the central part of the buttermaking procedure. It is a process of agitating the cream until granules of butter form and the butter separates from the buttermilk. Colour is added to the butter in the churn and the butter granules are washed before they are

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12 The cream is allowed to stand for varying lengths of time with or without the addition of a starter culture to allow it to "ripen" or develop the desired flavour of butter.

"worked" or kneaded into a compact mass and salt added if required.

When the more traditional buttermaking technology is used, the skill of the buttermaker is vital to the quality of the end product. This skill is particularly in need at the "working" stage where the butter granules must be worked into a mass which is firm and waxy but not greasy and with no visible droplets of water.

The typical butter churn is a cylindrical drum on a longitudinal axis, but it may also have the shape of an inclined cone or irregularly shaped cube. Inside, there are usually agitators or baffles designed to agitate the cream violently. The churn is usually half filled with the cream and the decision to stop the churn is made on the judgement of the buttermaker. Processing requires about an hour.

However, with the increasing desire for large scale plants continuous buttermaking technology has become available. There are several varieties of continuous systems and though there are differences in design, the key feature is the speed at which these systems operate and the way they make redundant the skill of the buttermaker. Cream entering the system may be churned into butter in about 1.5 seconds

e) Cheese

Cheese, like butter, has its origins way back in ancient history. The ancient Egyptians are known to have made cheese by carrying milk around in pouches made from sheep's gut and slung over their shoulders. The rennet in the sheep's gut coagulated the casein in the curd, allowing the cheese to form.

In the cheese making plants, lactic acid or any other suitable enzyme of acid may also be used as an alternative to rennet, to coagulate the casein in the curd. The curd may be obtained from whole or partially skimmed cow's milk or the milk of other animals, to which cream may or may not be added.

In the manufacture of cheese, as with butter, the skill of the cheesemaker remains of vital importance in determining the quality of the final product. Unlike butter, however, cheese manufacture has not been mechanized and automated to any great extent. Cheeses have therefore tended to retain their peculiar regional and local characteristics which cause particular types of cheese to be associated with individual processes and specific locations.

Lampert (1975) points out that there are over 800 names of cheeses, although they are probably no more than eighteen distinct kinds. These are listed as:
Brick; Camembert; Cheddar, Cottage; Cream; Edam; Gouda; Hand; Limburger; Neufchatel; Parmesan; Pavolone; Romano; Roquefort; Sapsago; Suiss; Trappist; Whey cheeses.

It is also suggested that cheeses may be classified according to their texture (soft, semi-soft, hard, very hard) or according to the way in which the milk is "ripened" (by bacteria; by mould; by surface microorganisms; by bacteria combined with surface microorganisms, or unripened).

In general cheese making involves the classification of the milk, pasteurization (optional), standardization, ripening, colouring, adding rennet or other enzymes for coagulation, cutting and heating of the curd. At this point the agitation causes the curds to separate from the whey[13]. The rate at which the whey is allowed to drain away depends on the type of cheese being made. For soft cheeses the whey is drained and the curd removed quickly from the processing vat.

Cheddar cheese, a hard cheese, is the most universally made cheese. Cheddaring refers to the way in which the curd remaining after the whey is drawn off, is matted and piled, the final result depending very much on the cheese-maker's skill. The cheddaring is complete when the small curd particles are completely fused.

The curd is then "milled" or cut into thin strips and salted, placed with cheese cloths with hoops and into a cheese press to expel moisture. The drying process may take up to two days. Surface drying continues when the cheese cloths are removed and the cheese is placed on shelves and turned every 3-4 days to allow a rind to form on the Cheddar cheese.

Some attempts have been made to mechanize the cheese making process but this has been largely restricted to the "Cheddar" type of cheese. Some mechanical aids are also available.

Nutritionally, cheese is a good source of nitrogen and fat (fat content varies with type of cheese). It is

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13 Whey is the liquid remaining after the removal of most of the casein and fat from the milk in the manufacture of cheese. It is a good source of lactose, albumin and minerals.

usually a good source of calcium and phosphorus if rennet is used. When the cheese is made from whole milk, it is a good source of vitamin A and carotene.

f) Cultured and fermented milk products

Many milk products are made by allowing the milk to ferment and sour in a controlled manner. Various types of bacteria and yeasts (moulds) are used to cause the milk to produce lactic acid and ferment the product.

Special strains of bacteria are cultured and allowed to multiply. When added to the milk they produce a desired flavour and aroma in the product made from them. The product is made to sour to make it more easily digestible than is ordinary milk.

Products made by the addition of bacteria cultures include yogurt, sour cream, cultured buttermilk, Acidophilus milk and a Russian drink Kumiss.

Yogurt (yoghurt) is a Turkish type of lactic and fermented milk. The starter culture is a mixture of streptococcus thermophilus and lactobaullus bulgaricus which is added to homogenized and pasteurized milk. After incubation the product is cooled. Fruit or fruit and other ingredients and flavours may be added.

Sour cream is the result of the ripening of pasteurized cream with lactic acid producing culture and is used mainly for dressing salads.

Lactic acid bacteria are similarly used in the production of cultured buttermilk, where they are added to pasteurized whole or skim milk to precipitate fermentation.

Acidophilus and Bulgaricus milk are made to assist in the treatment of intestinal disorders although there is no consensus on their true value in this respect. Lacto-baccilus acidophilus and lactobacillus Bulgaricus are used respectively in the fermentation process.

With some products an alcoholic fermentation process may also be used. Kefir is one such product where Kefir grains[14] are used to ferment the milk. The Russian (and Western Asian) drink of kumiss, which is often made from mare's milk also derives from an alcoholic fermentation process.

g) <u>Traditional milk products</u>

In some parts of the world there are home produced milk products which have tended to remain as home made or cottage type products made using a traditional tech-nolocy. Such products may not be very well known world wide.

One such product is Khoa, an indigenous form of highly concentrated milk in India, used for making certain milk sweets. The milk to be concentrated is boiled in a vessel known as a karachi and agitated by hand using a brass or iron ladle (khunti). If aseptically packed in tins at a certain temperature (80-90°C) and moisture content (20-25%), the product is found to have a minimum shelf life of 14 days[15]. In the absence of aseptic conditions

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14 Kefir grains are small gelatinous particles which are made from the curdled milk containing the fermenting organisms.

15 See Warner (1976, p. 227).

deterioration of the product is swift.

The product, however, is usually made into sweets such as barfi by the addition of sugar or syrup with a variety of flavours, colours, dried fruits, nuts and spices. Another sweet, gulabjamum, has flour (usually arrowroot flour) added, is fried in ghee (an Indian form of butter) and steeped in a sugar syrup.

Some Indian researchers have argued the case for khoa to be given what they see as its rightful place among dairy products[16].

Channa or Paneer is another indigenous dairy product produced in homes in India. It is usually a skim milk product.

Many cheeses and cultured milk products are, as mentioned before, still produced in cottage industries using a traditional type of technology and therefore qualify for inclusion under the heading of traditional milk products.

3.2 Disaggregation of Fluid Milk Technology

Central to the approach being used in this thesis is the disaggregation of dairy Processing Technology to facilitate the use of engineering data in the construction of production and cost functions. In order to do this some rational basis for disaggregation must be found. This section is concerned initially with establishing a rational basis for the disaggregation of plant technologies in general and, subsequently, with the specific case of fluid

16 See Srinivasan and Rajorhia (1976).

milk technology.

3.2.1 A basis for disaggregation - The unit operations of food engineering

The sub-process concept has already been introduced in Chapter 2 in relation to the disaggregation of plant technologies for previous engineering studies. The idea is that it is possible to take a plant process and break it down into its constituent activities or sub-processes. There is, however, no universally accepted set of criteria for identifying a sub-process or for limiting the process of sub-division. It is essential, therefore, to establish some rationale for the sub-divisions that will be made in the case of fluid milk technology.

One possibility is to use the approach adopted by McBain (1970) in his study of footwear manufacture (see Chapter 2), in which the sub-processes are delimited by the points in the overall plant process where material transfer takes place. This is the "work station" concept favoured by the economists at the David Livingstone Institute. In general, it is only when the material is moved physically from one identifiable work point to the next, that one sub-process ends and another begins.

This seems reasonable enough for plant processes where there are obvious discrete activity centres with gaps in between when the material is simply in transit. This is appropriate in the case of many plant processes and is particularly applicable to the types of industries considered by the group mentioned above (cloth, sugar, grain, etc.). It is, however, not quite as reasonable a basis for the type of continuous process that is involved in dairy processing. The product may move continuously through the plant and chemical changes may be occurring as the product is in transit. Thus, in the case of chemical process industries, the approach described above, though useful, is not strictly applicable.

The Markowitz-Manue "task" approach to disaggregation, discussed in Chapter 2, which distinguishes the "tasks" to be performed in the metal working plants, is again useful though not very appropriate in this case. The emphasis on the individual task or operation being performed does have some relevance to the way in which dairy processing technology may be disaggregated. The tasks or operations in the fluid milk plants, however, are not as independent and complete in themselves as in the metal working industry and so account must be taken of the way in which they link together.

In view of the peculiarities of the particular type of processes involved in the fluid milk plant, the most sensible approach to disaggregation seems to be one in which the principal unit of analysis (or sub-process) is closely related to the unit operations of food engineering. This provides a basis which can be used for analysis of other food processing industries and eliminates the problem of considering break points in the production process.

Unit operations in food processing may be grouped into broad categories which generally cover four main types of operations - preliminary, conversion, preservation and ancillary. Brennan (1969) in his work on food engineering identifies, in all, eighteen sub-groups of these four, which, in turn, are further subdivided. Some of the more relevant of these have been extracted and are listed below.

a) Preliminary Operations

i) Raw Materials and the Process

I) Selective breeding of raw materials

II) Growth programming and contract purchasing of raw materials

III) Transportation of raw materials

IV) Storage of raw materials

ii) Cleaning of Raw Materials

I) Removing contaminants in food raw materials

iii) Sorting and Grading

I) Sorting by weight, size, shape, colour

II) Grading of foods

b) Conversion Operations

i) Size reduction and Screening

I) Slicing, dicing, shredding and pulping

II) Comminution of solids

III) Screening

ii) Mixing and Emulsification

I) Mixing

II) Emulsification

iii) Filtration and Expression

I) Filtration

II) Expression

iv) Centrifugation

v) Crystallization

I) Nucleation

II) Crystal growth

III) Polymorphism

IV) Crystallization involving separation

V) Crystallization not involving separation

vi) Heat Processing (1)

I) Heat transfer

II) Heat generation for heat processing

III) Application of heat to food

IV) Food conversion by heat processing

c) Preservation Operations

i) Heat Processing (2)

I) Microbiological considerations

II) Pasteurization

III) Sterilization in containers and on containers

IV) Sterilization outside containers

ii) Evaporation

iii) Dehydration

iv) Freezing

v) Irradiation

vi) Food storage

vii) Filling and sealing

d) Ancillary Operations

i) Plant sterilizing and cleaning

ii) Water purification and waste disposal

iii) Materials Handling

I) Conveying, elevating

II) loading on trucks, stacking

All of the eighteen (18) sub-groups of operations listed above are represented within the dairy products industry. As the scope of the analysis is narrowed to fluid milk products and to pasteurized milk in particular, some of the sub-groups are no longer relevant entirely and some of the sub-divisions of these sub-groups do not apply. Furthermore, the scope of the study excludes certain activities from being considered. For example, because the analysis is restricted to in-plant operations, the selective breeding of raw materials, growth programming and contract purchasing operations are excluded. The transportation of raw materials is included since this affects the reception operations.

The food engineering operations list may now be rewritten for a pasteurizing plant, specifically, defining sub-processes and their sub-divisions more precisely. The same four broad groupings are retained.

a) Preliminary Operations

i) Raw materials and the process

I) Transportation of the raw milk

II) Buffer storage of the raw milk

ii) Cleaning of the raw milk

I) Clarification or filtering

iii) Sorting and grading

I) Testing for butterfat etc.

II) Weighing and recording.

b) Conversion Operations

i) Mixing and Emulsification (only in recombining plants)

ii) Centrifugation (for standardization and clarification)

iii) Size reduction

I Homogenization (reduction of size of fat globules)

iv) Heat Processing (1)

I) Heat transfer - cooling of milk

c) Preservation Operations

i) Heat processing (2)

I) Pasteurization

ii) Irradiation

iii) Temporary storage

iv) Filling into containers

d) Ancillary Operations

i) Plant sterilization and cleaning

I) Equipment sterilization and cleaning

II) Container sterilization and cleaning

ii) Materials handling

I) Conveying

II) Casing and stacking

III) Loading out, in.

3.2.2 Sequential operations - the stage concept

The nature of fluid milk processing, as with many other types of products, is such that the operations must be performed in a given sequence. There are some areas where the order may be altered depending on the type of technology being used in the plant. An example of this is found in the cleaning of the raw material operation (i.e. removal of sediment from the milk) which may take place at slightly different points in the general sequence depending on the technology being used. This becomes much clearer in Section 3.3.

The general sequence of operations performed in plant producing pasteurized market milk follows closely the order given in the broad categories in Section 3.2.1. Some of the ancillary operations given as the fourth grouping are actually activities performed along with the preliminary, conversion and preservation operations and not simply at the end of the sequence (e.g. conveying).

Once these ancillary operations are inserted in their correct position in the sequence of operations, it is possible to view the progress of the product from raw material to finished product in a series of stages. The separate sub-process modules or stages form the basis for the engineering analysis to give production functions for the alternative technological systems which may be used at each stage.

The operations listed in Section 3.2.1 may be further modified and rearranged to give roughly the general sequence of operations in a pasteurizing plant with liquid raw milk input, as follows:

a) Preliminary Operations

i) conveying of raw milk into plant

ii) Weighing and/or measuring raw material

iii) Testing for quality (butterfat, etc.)

iv) Cleaning and sanitation of reception containers

v) Temporary storage of raw milk (heat transfer operation - cooling - may be necessary).

b) Conversion Operations

i) Heat processing (1) - Heat transfer (preheating of milk)

ii) Centrifugation (for standardization/removal of sediments)

iii) Filtration and expression (removal of sediment - if not done in vi) above - position varies)

iv) Size reduction (of fat globules) - Homogenization (optional, position varies)

c) Preservation Operations

i) Heat processing (2) - Pasteurization, or

ii) Irradiation (alternative form of treatment)

iii) Temporary storage (buffer)

iv) Filling into containers

v) Container sterilization and cleaning (bottle washing)

d) Ancillary Operations (to follow sequence above)

i) Casing, stacking and loading

ii) Plant sterilization and cleaning

It may be noted that whether certain operations are included or omitted this may affect the final characteristics and quality of the milk. The homogenization process, if included, imparts to the final product a peculiar set of characteristics different from those found in non-homogenized milk. Similarly cleaning the raw milk by a centrifugal process removes more of the impurities than when the milk is simply filtered. Hence this raises the issue of technological determinism[17]. It will be shown, however, that price decisions are made on the principal characteristics of the final output, there are alternative ways of performing what is essentially the same operation.

This is discussed in fuller detail in the section which follows.

3.3 Technological Alternatives for Individual Operations

The alternatives (where they exist) may be examined for each operation. However, it will be found that certain operations tend to form a group such that the technological alternatives may be better related to the group than to each operation individually. Thus it becomes possible and more practical to consider as a <u>stage</u> a group of related operations rather than every individual operation in the sequence. This becomes clearer as the alternatives are explained.

3.3.1 Preliminary operations

a) Conveying of milk into the plant

The type of technology used for bringing the raw milk into the plant depends, first of all on the way in which the

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17 See Chapter 1.

raw milk is brought to the plant. Milk may be brought to the plant in

i) bulk tankers

ii) cans.

i) Bulk tanker

Milk delivered by bulk tanker is conveyed into the plant by a discharge line from the tanker. The milk may be allowed to flow by gravity or it may be pumped. It is difficult, however, to separate this conveying operation from the second operation - weighing and or measuring of the milk being discharged. This connection is demonstrated in (b) below.

ii) Cans

Milk received in cans may be conveyed in by lifting, by gravity roller or by powered conveyor. Again the actual choice of conveyor system depends on the type of weighing technology being used.

b) Weighing and/or measuring raw material

i) Bulk Tanker delivered milk

Weighing at the plant may be done by

I) Weighbridge - In this method the empty weight of the tanker is subtracted from the full weight to determine the weight of the milk. In this case gravity flow, or pumping may be used to convey the weighed milk through the line from the tanker into the plant.

II) In line metering - In this case the milk is conveyed into the plant by pumping it through the line. An in-line milk meter measures the milk as it is pumped through the line.

III) Load cells[18] - The raw milk is usually pumped from the tanker into special storage tanks which are fitted with load cells to indicate the weight of the milk.

Hence whether gravity-drawn or pump-drain conveying is chosen, must depend to some extent on the type of measuring or weighing system that is used. Gravity flow would be largely incompatible with the use of in-line metering for example. Thus, the two operations may be considered together as a single stage. This also applies to can delivered milk.

ii) <u>Can delivered milk</u>

Can delivered milk may be weighed by

I) Hand tipping of the milk from the can into the weigh tank and manually recording the weight on a dial scale. This manual type of technology is compatible with the cans being conveyed on gravity rollers.

II) Use of a cradle dump, a device used to assist in speeding up the dumping of the milk into the weigh tank. With this system, a recording scale[19] rather than a dial scale is used, as this is a quicker system. With this faster system, a power conveyor is required.

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18 A storage tank is mounted on load cells, which electronically activate a recording device which indicates the quantity of milk in the tank.

19 A recording scale prints out the weight of the milk in the weigh tank.

III) Automatic tipping and recording - A completely automatic system which requires a power conveyor.

The milk is tipped into a weigh tank which may have one or two components with sloping bottoms leading to discharge gates. For the manual system, the weigh tank is suspended from a weighing machine with a dial calibrated in weight or volume or both. The checker manually records the weight. The recording scale prints out the weight.

iii) Testing for quality

Where milk is delivered in cans the can lids may be removed and the milk checked for visible filth and undesirable odours. Tanker delivered milk may be checked on the farm. Sediment testing may also be done.

The most usual test is the test for butterfat. For this the Babcock test[20] is generally used. Sampling may be automatic. Semi-automatic sampling devices may be attached to the weigh tank.

For manual sampling, a small portion of milk is removed from the weigh tank, placed in a jar and labelled. This would be compatible with manual tipping and weighing of can delivered milk.

c) Cleaning and sanitation of reception containers

i) Bulk tanks

After the milk has been drained from the tanker truck, the inside of the tank must be cleaned and this is

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20 This is a popular method of testing the butterfat content of the milk by measuring the cream line in a special test bottle.

usually done at the dairy, either by a special worker or by the truck driver. Parts of the tank are dismantled (manhole cover, drain valve) and the interior washed out. This operation need not be closely related to the methods used in discharging and measuring the contents of the tank.

ii) Cans

Cans are usually washed immediately they have been emptied, and are conveyed directly to the washer or washing area from the tipping points.

In a manual can reception system, the tops are removed manually and conveyed separately to the washing point.

In a mechanical or automatic system, the tops are removed mechanically and conveyed on a power conveyor at the same speed as the conveyor to the tipping point.

The cans are drained before being washed. When tipping is done manually, the can is held upside down for several seconds before being passed on for washing. For the faster tipping systems, the can, after being tipped, is placed upside down on a rack, and drains into a pan on its way to the washing point. The contents of this pan are channelled into the weigh tank.

The actual washing of the cans may be done manually or mechanically.

I) Manual washing - The cans are washed by hand and are then usually held over a jet of steam for sterilization. This is compatible with manual tipping.

II) Mechanical washing - Rotary or "straight-through" types of mechanical washers may be used. In the slower rotary system, the cans when placed in the washer, travel in a circle over water, detergent, and air appropriately ordered.

The "straight-through" washer is a tunnel type where the cans enter and leave on opposite sides. It is a faster system.

Some mechanical systems may actually be manually assisted. Some small rotary washers must be turned manually for the cans to pass over the respective jets of cleaning solutions and rinses.

d) Temporary storage of raw milk

In between the receiving of the milk and the performing of the conversion and preservation operations, there is usually some provision made for buffer storage. This is intended primarily to even out the flow on the other side, since the reception rate of the raw milk may not always be completely synchronized with the desired rate of the core processing operations. In addition, the buffer storage is intended as a hedge against breakdown of the plant.

Storage is done in large tanks which may be horizontal (for smaller dairies) or the larger vertical silo type. The choice is mainly in terms of which size is appropriate for the reception and processing schedules in the plant.

The milk to be stored must be cool ($4^{O}C$ or $29^{O}F$). When milk is received by tanker, the milk is usually cool enough to be conveyed directly to storage without further cooling. This is because the milk destined for bulk collection, is stored on the farm in refrigerated tanks. Little heat is gained in transit, but in some plants the milk is passed through a cooler before storing anyway.

The temperature of milk received in cans is usually much higher. As a result the milk is usually passed through a cooler (a heat exchanger) before entering the storage tank.

The cooler may be a cabinet type of plate type, the choice depending on the space available. Cabinet coolers are a series of surface coolers (a series of horizontal tubes enclosing cooling medium) placed close together.

In plate type coolers, cold water or refrigerated brine is circulated between the plates. This is the more popular type and is illustrated in Chapter 6 (Fig. 6.2).

3.3.2 Conversion Operations

a) Heating processing (1)

The milk is usually preheated before the main presentation operation is performed. It may be noted, however, that with the more advanced technology, the preheating may be done in the one equipment unit that also does the preservation operation (pasteurization).

This preheating is done mainly to facilitate the centrifugation and/or filtration processes which follow for the removal of sediment and impurities from the milk.

Thus the choice basically is one of having either a separate heat exchanger, usually of the tubular or plate type, with the batch technology or a more advanced technology (such as the HTST system) where the preheating is an integral part of the process.

b) Centrifugation

A mechanical clarifier, which is similar to the cream separator discussed in Section 3.1.1.d, may be used to remove sediment and impurities from the milk by centrifugal force. The clarifier removes dirt, body cells, leucocytes and some bacteria.

Where it is customary to ensure that the milk has a standard amount of fat, a single piece of equipment, the standardizer clarifier may be used.

The choice is not so much which type of clarifier to use, but is essentially one of whether a clarifier should be used in place of a filter. A clarifier is substantially more expensive than a filter, but at the same time it removes not only dirt and sediment but also leucocytes and some bacteria and thereby leaves a "cleaner" product (i.e. a commodity with different characteristics). Additionally, where a standard product is required, the combined unit might be worthwhile.

In ensuring that the question of choice of technology is not simply a question of choice of product characteristics it would be necessary to make some assumptions about whether the milk will be standardized or not standardized and whether it will be clarified (mechanically) or simply filtered, as these are not strictly alternatives for producing an identical commodity.

c) Filtration and Expression

In removing sediment by filtration, the milk is strained or filtered through filtering cloths and the particles removed by straining them out. It is useful for removing the visible evidence of contamination from the milk but unlike clarification, the filter process does not remove microorganisms.

As with preheating, the filtration operation may be part of the system of equipment used for the pasteurization process (HTST), with a filter fitted with the unit between the preheating section and the pasteurization section.

Thus once it is decided that a filtered, rather than a clarified product is desired, the choice of separate filter or in-line filter would depend only on the pasteurization system to be used.

d) Size Reduction (of fat globules) - Homogenization

As mentioned previously, this is a completely optional operation, its presence or absence depending solely on the desired characteristics of the final product.

The homogenizer is, like the clarifier, an expensive piece of equipment and clearly the decision to use it must relate to the type of market into which the product is being sold. A description of the homogenizer and the principle on which it operates have already been given in Section 3.1.1.c, along with a discussion of the advantages and disadvantages of its use.

If homogenization should be considered desirable then, depending on the pasteurization system, it may be a separate individual unit through which the milk is directed before pasteurization or it may be incorporated in the more advanced technological systems as part of a continuous flow system.

Usually, however, the homogenization is done after preheating but before pasteurization. The fore-warming of the milk facilitates homogenization and since the homogenizer may be an additional source of contamination, the homogenization is done before the final high-head stage of pasteurization.

It seems reasonable, therefore, to consider all the conversion operations, with the preservation operations to follow as a single stage in the process, since, once the characteristics of the product are decided, the technological choice is limited to a two system, linked to the pasteurization technology, and requiring compatibility among them.

3.3.3 Preservation Operations

a) Heat processing (2) - Pasteurization

Some aspects of pasteurization technology have already been discussed in Section 3.1.1.a. The choices available will now be examined more closely.

The choice of pasteurization technology lies essentially between a batch processing system and a continuous one. In the continuous systems, there is a choice again between different time-temperature combinations, as discussed earlier. The high-temperature-short-time (HTST) system is the most advanced technology and, of course, the most easily obtainable.

Although these different processing technologies use different time-temperature combinations, they can be considered alternatives for producing a product with the same characteristics. This is because these various combinations stipulated by law all produce the same commodity defined as a pasteurized product.

i) Batch pasteurization

This is a discrete process, where a batch of milk, after having had the conversion operations performed, is heated, held and partially cooled in a vat (or vats). It is a long-hold process where the milk is heated to at least $60^{\circ}C$ ($140^{\circ}F$) and held for at least thirty (30) minutes. Much care has to be taken with this type of system to ensure the temperature does not rise above about $65.6^{\circ}C$ ($150^{\circ}F$), at which the milk may acquire a "cooked" flavour, thereby affecting the final characteristics of the product.

The entire operation may be done in a single vat or if a faster rate is desirable, separate vats may be used for heating and cooling. These vats are usually jacketed vats where the vats are double-walled and hot water or steam is circulated between the inner and outer walls to effect the heating of the milk. For cooling the hot water is replaced by cold water.

These vats are mainly of two types, the spray vat and the coil vat. In the spray type, the water is forced (sprayed) through holes in the pipes between the two walls, while the milk inside is gently agitated by moving blades attached to the top of the vat.

Where a coil vat pasteurizer is used the hot water passes through a coil inside the vat, which heats the milk and agitates it simultaneously as the coil rotates.

This batch type technology is of an older vintage which is little used in modern factories in developed countries. However, the vats can still be made and so they should be evaluated as an alternative which might be appropriate in a particular economic environment.

ii) Continuous flow (non-HTST)

In the continuous flow system, the heating, holding and partial cooling is all done as the milk is in transit through a series of pipes (or tanks). The length of the pipes is such that the whole process is completed in the time it takes for the milk to flow through from one end to the other.

Lampert (1975), puts the time needed for the complete heating and holding procedure as thirty (30) minutes. An FAO (1953) study estimates the filling time for the vessels, where tanks are used, of fiften (15) minutes.

The initial heating before, and the cooling after, pasteurization may be done regeneratively where a system of pipes are used, the cool incoming milk cooling the warm outgoing milk and itself being warmed by it.

iii) High-temperature-short-time pasteurization

This is the most advanced technological alternative for effecting pasteurization. It is a continuous flow process similar to (ii) above but much faster, with a pasteurization holding time of 15 seconds, and with a higher temperature of 71.7°C (161°F).

The milk may flow over plates, with the heating medium flowing in the opposite direction on the other side, or alternatively it may pass through tubes in a steam heated cylinder.

This type of system, as explained earlier, does incorporate many or all of the conversion operations described under (b) above. Figure 6.5 (a) describes an HTST system, with a regenerative feature.

The HTST system requires only 1-3 minutes for the entire process and is favoured for the modern high-speed processing plants.

It may be noted that cooling (to (4.4°C) after pasteurization is required. This may be considered as a separate heat exchange operation. In the batch, and the continuous (non-HTST) system the milk has finally to be passed through a plate or cabinet cooler (heat exchanger) similar to that described under Section 3.3.1(d) above.

Some HTST systems are close to 100 percent regenerative and no further cooling is required once the milk leaves the regenerative section of the pasteurizer system.

b) <u>Irradiation</u>

Irradiation is an alternative to pasteurization, for removing the bacteria from milk. The required ionizing radiation may be obtained from an electron beam from a special type of machine or from gamma rays from a radio isotope.

Lampert (1975) points out, however, that in the U.S.A. the radiation of foods is not permitted. Additionally, the process is said to produce off flavours in the milk.

Thus this alternative to achieving milk free of harmful bacteria is not being actively considered any further, but its existence may be noted. Other less acceptable forms of treatment include the use of ultra-violet lights, and of hydrogen peroxide.

c) Temporary storage (buffer)

Temporary storage serves much the same purpose, and is of the same type as described in sub-section 3.3.1.(d) above. The storage is designed to hold the cooled pasteurized milk, without deterioration for a period sufficient to iron out any unevenness in the flow from the pasteurization to the filling stage.

Where pasteurization is in discrete quantities (batch) the capacity of the buffer storage is very critical to the smooth operation of the filling process, which is likely to be of the continuous type.

d) Filling into containers

The choice for the filling operation is primarily one of selecting the type of container into which the milk is to be filled. The scope of the analysis is limited strictly to the provision of milk for households, and so bulk containers are ignored.

The alternatives considered are:

i) glass bottles

ii) paper cartons, and

iii) plastic bottles.

i) <u>Glass bottle filling</u>

In filling the milk into glass bottles, two basic types of technology may be considered - manual or hand-operated fillers, and fully mechanical fillers.

In the hand operated fillers, the operator assists in controlling the filling and capping operations.

The continuous mechanical fillers are basically of either the gravity-type or the vacuum-type.

In the gravity type the milk flows under gravity from the valves at the bottom of the filler bowl in a timed process with an unloading starwheel removing the bottle from the filler valve and placing it under the capper. It is then conveyed to the point where it is packed.

It may be noted that the conveying of the bottles is considered an integral part of the bottling system and will be treated as such rather than as a separate operation.

The vacuum-type filler is similar to the gravity filler except that the milk is drawn into the bottle by vacuum. In this case the machine will not fill broken bottles.

In the case of glass bottles, the container costs cannot be considered simply in terms of the unit cost of each container filled. Since bottles are returnable and have some estimated life (number of trips), this must also be taken into account in the computation of container cost.

Additionally, it must be considered that the bottles must also be washed and sterilized, and that an additional off-loading and conveying operation is required (discussed in 3.3.4(a) below).

ii) Cartons

Paper cartons come in two main types - those that are formed at the dairy and those that are available pre-formed. The form-fill-seal machines which form the container around the milk in the dairy is generally used for the packaging of sterilized milk.

The carton filling technology is primarily of a mechanical nature. The pre-formed flattened containers are usually opened, filled and fully sealed mechanically, using heat sealing techniques.

The cartons, usually made of wax or plastic coated paper, are disposable and so are used only once. No washing operations are involved.

iii) Plastic bottles

Plastic bottle filling usually involves the installation of equipment to first manufacture the plastic bottle. These bottles, shaped very much like glass bottles, are made from a granular plastic material which is melted and formed in the bottle making machine.

A special plastic bottle filling machine fills and caps the plastic bottle.

As with paper cartons, these bottles are disposable and used only once. The cost of manufacture and purchase of raw materials must be taken into account in a comparative cost analysis.

e) Container sterilization and cleaning

This applies only if glass bottle filling is chosen under (d) above.

Bottle washing may be manual or mechanical. Bottles may be hand washed and then dried over hot air or a washing machine may be used.

The washing machines are of two basic types - i) the jet type - where a series of jets spray rinsing and washing solutions inside and outside of the bottles and ii) the soaker type where the bottles are soaked in different solutions as they are conveyed on a moving apron through the proper sequence of solutions.

These washing machines may also be described as rotary or "come-back" types for smaller dairies where the bottles enter and return from washing at the same point, and the "straight-through" or tunnel type used in larger dairies.

3.3.4 Ancillary Operations

a) Casing, stacking and loading

For bottle and carton filling, the choice lies mainly between manual and mechanical casing, stacking and loading technol ogies.

The bottles and cartons may be picked up manually after they are filled and placed in the appropriate cases, after which they may be manually stacked and either lifted or pushed out or to storage on a trolley.

Mechanical casers are also available. These pick up the bottles or cartons in the appropriate groups determined by the size of the case and deposit the containers in the case.

The packed cases can also be stacked mechanically, using stackers which pile the cases up (usually from off a conveyor) so that they are ready for loading out or to be conveyed to storage where necessary.

The actual loading may also be done manually or with several mechanical aids such as the fork-lift truck and various types of loading equipment which may be driven or pushed around the plant to be deposited in some appropriate position in the stacking area or on the truck for the market.

This area is considered as the one with the greatest scope for choice of factor combinations. There is usually a fairly wide choice between men and machines.

b) Plant sterilization and cleaning

With this ancillary operation there is a choice between dismantling of the equipment for manual cleaning or use of a special circulating system.

The equipment for the other operations may be designed to use the special circulatory system known as Cleaning-in-place where water, detergents and various cleaning aids are circulated through the plant in a controlled manner to effect cleaning with the machines remaining in place.

The alternative is the manual cleaning of tanks and pipes which requires dismantling the equipment, the cleaning and scrubbing by hand and the reassembling of the equipment.

These operations have been described only to show the types of alternatives which may be discovered. The method of estimating the engineering production function and estimating costs will be dealt with in Chapter 6.

An important feature of fluid milk plant technology is that there are links between the individual operations or stages. They tend to depend in various ways on each other. In view of this, some method has to be found to allow the economic evaluation of the alternatives at the level of individual operations or stages, to be extended to the plant level. The technique of Dynamic Programming can well serve this purpose, and the following chapter explains the technique.

CHAPTER 4

DYNAMIC PROGRAMMING AND PROCESS OPTIMIZATION

The search for an optimal (in this case, least cost) technology at the plant level can be a complex and time-consuming exercise. The major complications arise as a direct result of the way in which the overall plant technology is, in reality, a composite of several sub-process technologies, usually with a plurality of alternatives at each sub-process (stage, task, work-station, etc.).

In the early engineering studies, discussed in Chapter 2 (Chenery, 1949; Cookenboo, 1955) a single process was being considered without the complication of sub-processes (or stages). Complications arise when attempts are made to analyse process plant technologies which involve several stages with different types of processing equipment and methods at the various processing nodes along the stream.

In studies of plant technologies, it was shown in Chapter 2, that there was a tendency either to optimize each sub-process in isolation, assuming complete independence of the choices at each stage (Stewart, 1975; Bhat and Pandergast, 1977) or to consider all the feasible combinations of the sub-process variants (Forsyth, 1977). In using the former option much of the realism is unnecessarily sacrificed by ignoring the interrelationships whereas the second option could be very time consuming when the number of feasible combinations is large.

The Dynamic Programming technique offers a procedure for optimizing a staged process in a way which overcomes these drawbacks, and those associated with the use of standard optimization techniques, where a large number of variables and constraints are involved.

As the Dynamic Programming approach to optimization is still relatively new and is not extensively used by Economists outside the Operations Research area, this chapter provides a broad-based introduction to the technique, in preparation for its application later in the thesis.

The first section reviews the origins and the character of the technique, and this is followed in a second section, by an explanation of the terminology and the nature of the interrelationships which characterize this optimization technique.

A third section deals with the formulation of optimization problems for the Dynamic programming of a solution and, in the final section the algorithms for obtaining a solution to the special type of process relevant to this study are examined.

4.1 The Origins and Character of Dynamic Programming

Dynamic Programming is a computational technique used for studying sequential decision problems and to optimize systems characterised by non-linear relationships. Like the more familiar Linear Programming Technique, Dynamic Programming (D.P.) represents an approach to reducing the effort required in locating the optimum point in a system by systematizing the search for that optimum. Unlike Linear Programming, however, D.P. is not a particular computational procedure for solving a specific type of optimization problem, rather, it is a technique for solving a wide range of optimization problems and the appropriate algorithm for a solution must be found for each.

The technique is generally associated with the work of Richard Bellman[1] and his colleagues at the RAND corporation Bellman is credited with having developed the idea that led to Dynamic Programming being used as a computational technique and much of the early work using the technique was carried out at the RAND corporation.

The concept of D.P. is based on the decomposition of an overall optimization problem with many variables, into a series of simpler individual problems (or stages) each possessing only a few (and in the extreme, one) of the total number of variables in the larger problem.

The technique works in a way such that by optimizing the more simple component sub-problems or stages in a particular manner, leads to the optimal solution of the larger more complex, problem. The simplification of the optimization procedure is effected by application of Bellman's "Principle of Optimality", by which the determination of one variable, leaves the problem with one less variable to be determined at the next stage.

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1 Richard Bellman's (1957) text was one of the earliest major work on the application of Dynamic Programming to a wide range of optimization problems.

Bellman (1957) explains this new "Principle of Optimality" by saying that:

"An optimal policy has the property that, whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

It is in this "Principle of Optimality" that the uniqueness of Dynamic Programming lies. As a means of solving discrete optimization problems, it is completely different from the principle of optimality employed in the standard more popular approach to solving discrete optimisation problems - the Differential Calculus approach.

In using the Differential Calculus approach, a discrete optimisation problem is decomposed into a set of equilibrium equations which are then solved simultaneously to obtain the optimal values of the variables. In this case the equivalent principle of optimality is that certain derivatives are zero.

One problem with the use of the differential calculus is the difficulty of establishing the global minimum (or maximum) rather than a local minimum (or maximum), even where only one variable is involved.

This type of problem with the differential calculus is well known and need not be reiterated here in its entirety. It is useful, however, to recall that for a function $y = f(x)$ as in Fig. 4.1, setting $f'(x) = 0$ and testing the value of $f''(x)$, the second derivative, would not indicate that the global minimum is at V. Furthermore, the formula for $f(x)$ should reveal that there are really two separate formulas

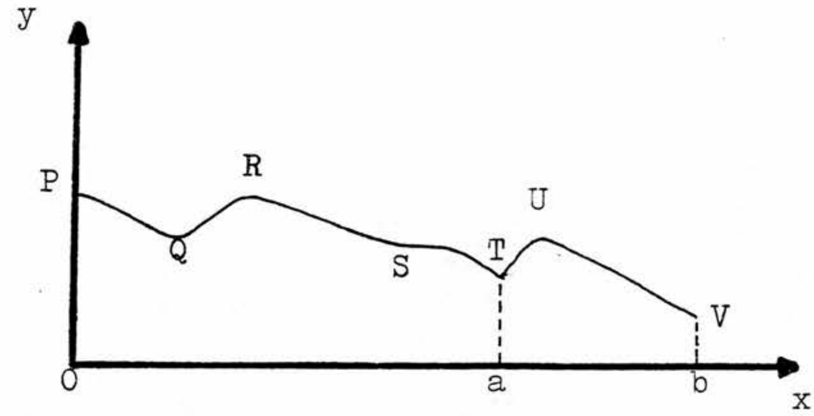

Figure 4.1 - The function $y = f(x)$

for the intervals Oa and Ob and that at $x = a$ the function is not differentiable. Thus finding the global minimum would involve finding the values at the end points of the function (P, T, V) and comparing these with the local minimum Q (S is an inflexion point).

The situation becomes even more intractable when there are more variables than one. All the first derivatives have to be made equal to zero, then the definiteness of the matrix of second derivatives established at each solution, and the boundaries of each region of differentiability searched for comparison with the internal extrema.

The Dynamic Programming method has a distinct advantage where there are several variables and the problem can be disaggregated so that the variables may be considered individually in the sub-optimization procedure (see Section 4.2).

In addition, D.P. does not suffer from the rigidity of the Linear Programming approach, where the relationship between the variables must be linear and where the constraints (decisions) must also be linear.

D.P. therefore provides a much more flexible approach, for handling the wider variety of data forms (numeric, descriptive) found in processing industry studies. The decision at one stage may be the choice of processing temperatures or throughput rates and at another it may be choice among different types of equipment, which may be difficult to evaluate within the calculus framework or as a linear or integer programming problem.

D.J. White (1969) considers the Dynamic programming approach to be, in a sense, a dual form of the Differential Calculus approach, since the optimality principle in Dynamic Programming is expressed not in terms of the solution variables, but in terms of their consequences via a value process. This is because, in the embedding procedure used in the Dynamic Programming technique, what is important is the consequence of the results up to that stage, for the values at the next stage of the process. This is explained in more detail in Section 4.2.

The Dynamic Programming technique may also be used in the solution of continuous (as opposed to discrete) forms of optimization problems. It is often seen as a very valuable, though, in some cases, lengthy, alternative to the continuous optimization techniques of the Calculus of of Variations, and the Pontryagin's "Maximum Principle". Its value lies in that it provides a computational means of finding actual numerical solutions to problems where the use of the Calculus of Variations or the Pontryagin's Maximum Principle would prove extremely difficult to solve.

In general, in the continuous case, where the concern is with finding the function of a function, the difficulty usually arises in finding a solution to the partial differential equations, especially where there are multiple boundary conditions imposed.

It is quite usual to use the Calculus of Variations to find a solution to an optimization problem for determining a set of discrete variables $x_1, x_2, \ldots, x_m$ by taking the continuous form as the limiting form of the discrete. The problem then becomes one of determining an optimal function $x(t)$ of some continuous variable t. This approach avoids the burdensome computations of a discrete formulation, and after the differential equations have been derived, they could be solved by using discrete approximations to these final differential equations. It is in finding this solution that the problems arise.

An example from Bellman (1962, p. 185), restated by White (1969), demonstrates the type of problems involved in using the Calculus of Variations.

The optimization problem is to find a function $y(x)$ which minimizes the functional

$$\int_a^b F(y(x),\ y'(x),\ x)dx \quad .$$

This could conceivably represent a case where the aim is to find the optimal rate of use of a particular technology $y(x)$, with costs depending, not only on the rate of use but also on the rate of change in use from one stage to another

$y'(x)$. This model would be a continuous approximation to the real discrete case, with the rates of use having upper and lower bounds a and b.

Using the Calculus of Variations, the Euler equation is deduced[1], giving

$$\frac{\partial F}{\partial y} = d|dx(\partial F/\delta y') ,$$

which, in this case, must then be solved numerically. But, as Bellman points out, although the Euler equation is highly rated analytically, its computational feasibility is not at all satisfactory. The problems stem from the variational problem itself and from the Euler equation.

One of the major difficulties comes in dealing with a two-point boundary value problem. Using high-speed digital computers, it is relatively easy to solve a problem formulated so that there is only one boundary condition. For example, the only initial bound a may be set to give the initial value which the variable x may take (e.g. slowest rate of production) such as

$$y(x_o) = p_1 .$$

However when the second (or end) boundary condition is added, say

$$y(x_n) = p_m ,$$

the computational procedure breaks down because the approach to a solution requires the determination of $y(x_o + \Delta)$ for the value which cannot obviously be found, since although $y(x_o)$ has been specified, $y'(x_o)$ has not been[2].

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1 See Bellman & Dreyfus (1962, p. 188).

2 Loc. cit.

The computational procedure now becomes more difficult to manipulate.

Apart from these computational hitches more distressing problems arise when constraints are imposed on the nature of the optimizing function. For example, if for the functional given earlier, a constraint were placed on the derivative form of the variable say

$$|y'(x)| \leqslant p_1$$

(e.g. cost of changing intensity of factor use), then $\partial F/\partial y'$ does not exist and there is no Euler equation to be solved. It would apply only where the constraint was met, leaving a gap or gaps in the solution.

Furthermore, this procedure gives only the stationary points and the global minimum would have to be found.

Where the Pontryagin's "Maximum Principle" is applied to a continuous formulation of an optimization problem similar problems arise in finding a solution to the differential equations which have been derived.

The Dynamic Programming Computational procedure may be used to derive these differential equations. However, when using D.P., there is no need to go so far. The computational technique of D.P. may be applied to find a solution without getting involved in the differential equations and facing the consequent difficulties.

The D.P. technique, in using a staged optimization procedure, is particularly suited to handling the discrete formulation of a problem. It avoids the computational problems involved in the use of the differential calculus and, also avoids the difficulties associated with finding a solution when the discrete is approximated to the continuous for use of the Calculus of Variations or Pontryagin's "Maximum Principle".

The principle feature of the process under consideration in this thesis is that it is a naturally staged, sequential process. The D.P. staged optimization technique is therefore capable of exploiting this structural feature of the production process, in order to find an overall solution to what is, effectively, a set of sub-problems. The D.P. technique is particularly suited to handling an optimization problem complicated by a large number of variables (states) and a large number of constraints (decisions).

In the following section the nature of the D.P. optimization procedure and the basic concepts are examined. Attention is paid to the peculiar terminology of D.P., which is used later in the thesis.

4.2 The Nature of the Dynamic Programming Optimization Procedure

A major distinguishing feature of this optimization technique is, as mentioned previously, the way in which a large and more complex optimization problem is decomposed into a sequence of more simple sub-problems which are then optimized sequentially, using the stated Principle of Optimality.

One of the first conditions that must exist for D.P. to be applied, therefore, is that the particular problem must be decomposable into smaller component parts, each of which involves an optimizing decision and is structurally similar to the overall problem. These decisions involve the selection of one or more control variables at each stage in the sequence of stages. The decision transforms the system from one state to another and the overall optimum is achieved by finding the optimal contracted path.

The special concepts and terminology used, is briefly reviewed in the first subsection and then the staged procedure is examined.

4.2.1 The characteristics of the D.P. formulation

The problem is formulated in terms of a discrete set of "decision" points or nodes at which decisions are made to transform the state at one stage into a new state at the next. The way in which the new state is reached is determined by the transformation function. These terms are used in describing the dairy process at the plant level and so are discussed in some more detail.

a) Stage

a stage is simply a point in the system's operation that can be represented as a sub-problem of the overall optimization problem. The stages are handled sequentially and may represent points in time or nodes in a path through a system such as in a manufacturing process plant, where the decisions that can be made, depend on the position reached in the chain of sub-processes which constitute the overall process.

The stage concept is used simply to allow the decisions to be ordered. In the manufacturing process being analysed, the actual number of stages through which the raw material must pass, is known in advance of the D.P. procedure being started. In such a situation the system is classified as being of finite, known duration with a total of N stages.

There are, however, other variants of the problem, where the duration is finite but the actual number of stages may depend on the decisions taken. The duration may also be infinite. Before the computation procedure is decided, questions must be asked about the character and duration of the process so that the correct algorithm for that particular class of optimization problems may be found. The structure of the process, then, is very important in determining the actual computational procedure to be used.

The processing problem considered in this thesis may be described as discrete, finite, known (deterministic) and the stages are directed. The solution algorithm explained under Section 4.4 is appropriate only to a problem with a combination of these process characteristics.

b) <u>State</u>

The state is a condition, from among alternative conditions, which may exist at a given state and which is relevant to the future performance of the process. The states themselves, may be discrete - or continuous-valued, although the continuous form is usually an approximation to the discrete, in cases where it might facilitate the computations. In the D.P. method applied to Dairy Processing the states are allowed to remain discrete.

In some cases each state may be represented by a vector with the elements of the vector representing the various components of the state. It is acceptable that the components of the state vectors may vary from one stage to another, and although many examples of D.P. applications show the states being of the same type from one stage to another, there are procedures to handle states which vary according to stage the use of data in tabular form does allow great flexibility in the types of data to which D.P. can be applied.

If there should be r_n components of an input state vector at a particular stage n, then the state at that stage may be described by a vector

$$S_n = (s_{1n}, s_{2n}, \ldots, s_{rn}) \; . \; .$$

In this way the dimensions of the state vector are allowed to be different for each individual stage (n). In much of the earlier work in D.P., the state descriptors were mainly numerical values, but in general there are no rules about what should enter the state description, and so names of places or characteristics of intermediate outputs in a processing plant are quite legitimate.

c) Decisions, decision rules and policies

At each stage a decision (or set of decisions) has to be made. The decision is made with regard to the action that is to be selected from a given set of alternatives. Where the decisions to be made have several components, the decision set may be represented by a decision vector with, say, m elements,

$$D_n = (d_{1n}, d_{2n}, \ldots, d_{mn}).$$

A decision at a stage in a processing plant, for example, may have several components of the decision, with regard to different rates of processing, different temperatures and other such elements of choice.

Decisions at any stage may be made on the basis of those components of the state vector which are observable at that stage. By virtue of the definition of "state", this vector contains all the information that is relevant to that particular decision.

A "decision rule", at stage N, say, associates a particular decision vector D_N, with each possible state vector S_N. This may be written as

$$\tilde{D}_N = D_N(S_N)$$

where $\tilde{D}_N$ is a given decision rule.

The term policy refers to the rule or set of rules which govern the admissible decision or set of decisions for every state at every stage. White (1969) distinguishes two types of policies labelled "pure" and "mixed". A "pure" policy is defined as one which determines for each stage, for any state, a unique action to be taken from among the allowable actions, whereas a "mixed" policy determines, instead, a unique chance mechanism by which the ultimate action will be taken (as in Markov chains). In this thesis the policy is of the "pure" type.

A policy which specifies the same set of rules for each stage is called a "stationary" policy. In general, however, these decision rules will vary according to the stage and are circumscribed by the general overall policy. These changing decision rules are particularly pertinent to the type of process under consideration in this thesis. In a processing plant the decision at one stage may be the temperature at which the process should be carried out, while at another stage the decision could be the capacity, or the throughput rate at which to operate.

d) <u>The transformation function</u>

The transition function describes the way a decision made at a particular stage transforms the state at that stage into a state at the next subsequent stage. The function specifies the relationship between successive states and the transformation of states over the decisions made may be written as:

$$S_{n+1} = T_{D_n}(S_n)$$

where S_{n+1} may be taken to be the output state vector from stage n, or the input vector into the subsequent stage, and D_n is the decision vector at stage n.

With the operating policy having been determined and with the decisions or mechanism for decision making at each stage known, the state of the output at the final stage (N) can be deduced from the state of the input to the first stage in the staged optimization process by repeated application of the transformation to give

$$S_{N+1} = T_{D_n}(T_{D_{N-1}}(T_{D_{N-2}}(\ldots T_{D_2}(T_{D_1}(S_1)))))$$

where S_{N+1} is the output state from the final stage of the optimization process (N).

This expression for the transformation, is the generalised form which takes into account the fact that the transformation operator may vary from one stage to the other. That is to say, the transformation that takes place is stage (or time) dependent. In this case the process may be described as non-stationary as opposed to a stationary process where the transformation function remains the same from one stage to another[1].

In the study of a production process, it is the non-stationary transformation process that is generally applicable. The decisions to be made and hence the transformation that takes place depends on the particular stage currently reached in the optimization process. In the case of the stationary process, the final state (output state at final stage) would be derived directly from the initial state with the transformation operator applied the appropriate number of times thus:

$$S_{N+1} = T^N(S_1)$$

where S_{N+1} is the output state from the final stage and S_1 is the initial input state at the first stage.

One important consequence of the way in which the transformation function relates one stage to those that went before, is the notion of the independence of the past. This means that when any state at stage m (m < n) is reached, the next state (in time) from the present state at m depends only on the state at m and does not require any knowledge of the past history of the system. Thus when any

1 See Bellman & Kalaba (1965, p. 12).

state at any stage is reached, the application of the transformation function sequentially ensures that the current state description includes all the information from previous stages relevant to the future stages. Thus the future is uniquely determined by the present.

This uniqueness theorem[1], is central to the economy of the D.P. staged optimization procedure, which, based on the previously defined "Principle of Optimality" allows the past stages, once optimized, to be "forgotten" as all that is important for future optimization is contained in the state information of the present stage being optimized.

The characteristics of the transition relationship extend to that of the "return" function (see 4.2.2. below) which the D.P. procedure seeks to optimize based on the "principle of Optimality". The analysis is done in relation to non-stationary processes, such as the one with which this thesis is concerned.

4.2.2 The optimization algorithm

The aim is to find the set of decisions which optimize some "return" or "objective" function. In this case, the aim is to find the set of optimal in-plant decisions with regard to choices at the sub-process level, which give an optimal value to the function. The nature of the return function is discussed and then the computational algorithm relevant to the particular type of process found in a manufacturing plant is discussed.

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1 Op. cit., p. 160.

a) <u>The "Return" function</u>

As the system moves from one node to the other, with the transformation operator converting one state into another as the decisions are made, a value can usually be attached to each point or node, depending on the path taken to reach that node. This path value has relevance only in systems which may be described as non-final-value system (as opposed to final-value systems). The type of value attached depends on the criterion of optimality and the characteristics of the "return" or objective function which is being optimized.

In the case of a non-final-value system, the objective is to find an optimal policy (i.e. set of decisions) that optimize a certain objective function. It is this type of system that is being considered in this thesis. In this system the optimization procedure requires the selection of the optimal decisions so as to maximize or minimize a prescribed scalar function of the state and/or decision variable. In a final-value system, the value of a policy is determined by whether or not a desired final stage is reached.

In the application of D.P. to production processes, the maximization of profits or minimization of costs are the usual forms of the criterion function encountered.

In the case of cost minimization, which is particularly pertinent to this thesis, the cost may be considered as a penalty attached to being in a particular (input) state at a given stage, and making a certain decision at that stage.

Thus, the individual stage return (cost) function may be written as:

$$h_n = h_n(S_n, D_n)$$

where h_n is the return or cost associated with the state at the individual stage n.

The principle feature of the overall n-stage return function in Dynamic Programming is that it is separable and piecewise continuous. Thus the total return from the complete process (N stages) depends on the returns $h_n(S_n, D_n)$ from each stage $n = 1, \ldots, N$ according to a functional relationship

$$R = g[h_1, \ldots, h_N], \text{ or,}$$

$$R = g[h(S_1, D_1), \ldots, h(S_N, D_N)] ,$$

and Dynamic Programming is applicable where there are relationships such that

$$g[h(S_1, D_1), \ldots, h(S_N, D_N)]$$
$$= \Big[g[h(S_1, D_1), g[h(S_2, D_2), \ldots, h(S_N,D_N)]\Big]$$

in order to satisfy the Principle of Optimality on which optimization by D.P. is based.

The aim is to maximize (minimize) the total return (penalty) from the N-stage process. Thus, using $f_N(S_N)$ to indicate the value of R using an optimal policy of over N stages from stage 1 to stage N, the objective function may be written as

$$f_N(S_N) = \max_{D_N} g\left[h(S_N, D_N) \circ \underset{D_1,\ldots,D_{N-1}}{f_{N-1}(S_{N-1})}\right]$$

where $$f_{N-1}(S_{N-1}) = \max_{D_{N-1}} g\left[h(S_{N-1}, D_{N-1}) \circ \underset{D_1,\ldots,D_{N-2}}{f_{N-2}(S_{N-2})}\right]$$

$$\vdots$$

$$f_2(S_2) = \max_{D_2} g\left[h\ (S_2, D_2) \circ \underset{D_1}{f_1(S_1)}\right]$$

$$f_1(S_1) = \max_{D_1} g\left[h\ (S_1, D_1)\right] .$$

all subject to $S_n = T_{D_{n-1}}(S_{n-1}) \qquad n = 2, N.$

In many cases, it is usual to have a return function that is separable additively, so that the operator $\circ$ in the above equations can be replaced by $+$. Thus, in general

$$f_n(S_n) = \max_{D_n} \left[h_n(S_n, D_n) + \underset{D_1,\ldots,D_{n-1}}{f_{n-1}(S_{n-1})}\right]$$

subject to $S_n = T_{D_{n-1}}(S_{n-1})$,

thus, from above, in order to find the optimal solution, $f_N(S_N)$, it is necessary first to find $f_1(S_1)$ which must then be substituted in $f_2(S_2)$ and so on to $f_N(S_N)$.

The functional equation is obtained using Bellman's Principle of Optimality, proof of which is provided in Appendix 4.1.

In the dairy processing problem, the objective function is the cost function, and this is to be minimized. Associated with each decision made at each stage, is a cost and the stage costs are separable (additively). The optimization takes place in the contracted manner of D.P. (see(b) below) so that the optimal decision for each stage is not necessarily that which gives the optimum (least) cost for that individual stage and state but for the contracted path (set of states) which led to the current point or node. Thus the relationships among the events and choices at the various stages in the production process can be taken into account.

For the type of problem being dealt with in this thesis, the methods for finding a solution are formalized in (b) below.

b) <u>Algorithms for a solution to the Discrete Deterministic Case</u>

For discrete deterministic processes, three different algorithms for finding a solution have generally been identified in the literature. These are:

a) Successive approximation in policy space

b) Successive approximation in function space, and

c) The direct method for directed stages.

Method c) above is the one which is appropriate to the type of process and system structure of the problem under consideration here and so will receive most of the attention here. The choice is also influenced by other characteristics possessed by a system which is already classified as having a deterministic transformation operator in its process structure. Other considerations include whether the process is stationary or non-stationary and whether the stages are finite (and directed) or infinite.

For a finite non-stationary process of the type associated with the dairy processing structure, where the number of stages for which the function must be evaluated is known, and where different decisions are made depending on the stage reached with the stages being directed in an orderly progression from one to the other, the means of finding a solution to both the value (objective) function and to the associated policy follow a precise form of sequential evaluation.

However, in cases where the process is stationary and the actual number of times the same decision(s) has to be made is uncertain, the algorithms of a) and b) above must be applied. These will be looked at briefly to show the difference between these approximation methods and the direct method employed here and the different situations in which they apply.

i) Approximations in function space

Consider a deterministic process, in which the number of stages is infinite, the return function may be written as:

$$f(S) \quad = \quad \max_{D} \left[h(S,D) + f\ T_D(S)\right] \quad .$$

Thus at the initial stage, the return function to be evaluated is

$$f_1(S_1) \quad = \quad \max_{D} \left[h(S_1,\ D_1)\right]$$

which means the $f_1(S_1)$ has to be estimated to be substituted into $f_2S_2)$ but because the states are not finite, the initial value of the function is unknown. The practice is to guess an initial approximation to $f_1(S_1)$ and then proceed recurrently to determine the subsequent approximation to the function

$$f_n(S_1) = \max_D \left[h(S,D) + f_n(T_{D_1}(S_1)\right]$$

for $n = 1, 2, \ldots$.

$f_1(S_1)$ can often be approximated from some physical or mathematical considerations.

According to Bellman and Dreyfus (1962), the $h(S_1,D_1)$, $T(S_1,D_1)$ and $f_1(S_1)$ the sequence should converge to a solution of the value function which is to be evaluated. This method of successive evaluation is designed to cut down on computation time which would be necessary if all the possible values which $f_1(S_1)$ could assume were to be taken into consideration in the computations.

This method can be applied to cases in optimal route type problems[1] and in relation to assortment and allocation problems and to inventory control. This technique, sometimes known as value iteration has its advantage in the $f_n(.)$ (for all states) converging to a limiting value $f(.)$[2].

ii) Approximation in policy space

This is a similar method to the one described in i) (above) and relates to problems with similar characteristics. This involves making a guess at the initial policy. They amount to much the same result in that the return function is determined by the optimal policy and conversely, the

1 See White (1969, pp. 8-15).

2 *Op. cit.*, p. 160.

optimal policy is determined by the return function.

The reason for first approximating the $D_1(S_1)$ (policy) which maximizes the initial return function $f_1(S_1)$ rather than guessing the return function is that for the particular process, there are intuitive approximations in policy space which are easily used.

This method similarly converges to a unique policy and return, again saving on computational time and effort. It can be applied to the same sort of problems mentioned in connection with the use of the approximation in function space technique.

iii) <u>The direct method for directed stages</u>

In Dairy Processing the system is such that the individual stages are connected in a series where there is no recycle of matter, energy or information from the output and of the system to the feed (input) end. In such a system, described as acyclic, the flow of information is in one direction only. Consequently, any change in the conditions imposed (decisions made) in one section can affect only that section and the ones downstream from it.

Thus with a typical non-stationary recurrence relation such as

$$f_N(S_N) = \max_{D_1} \Big[h(S_1,D_1) + f_{N-1} \max_{D_2,\ldots,D_N} \big[h(S_2,D_2) + h(S_3,D_3) + \ldots h(S_N,D_N) \big] \Big]$$

$$\text{or } f_N(S_N) = \max \left[h(S_N,D_N) + f_{N-1}(S_{n-1}) \right]$$

where $f_N(S_N)$ gives the value of the path from S_1 to S_N where optimization is done by a process of sub-optimization.

In the natural sequence in a plant, stage one represents the start of the process with S_1 being the state of the raw material input. The material flows downstream, where S_N is the final input state, S_{N+1} the state of the final material output, and S_1, the initial input state.

With the states being directed and finite the appropriate algorithm may be described as the Direct Method for Directed Stages. This method involves solving the basic recurrence relation directly.

$$f_N(S_N) = \max \left[h(S_N, D_N) + f_{N-1}(S_{N-1})\right]$$

$$\vdots$$

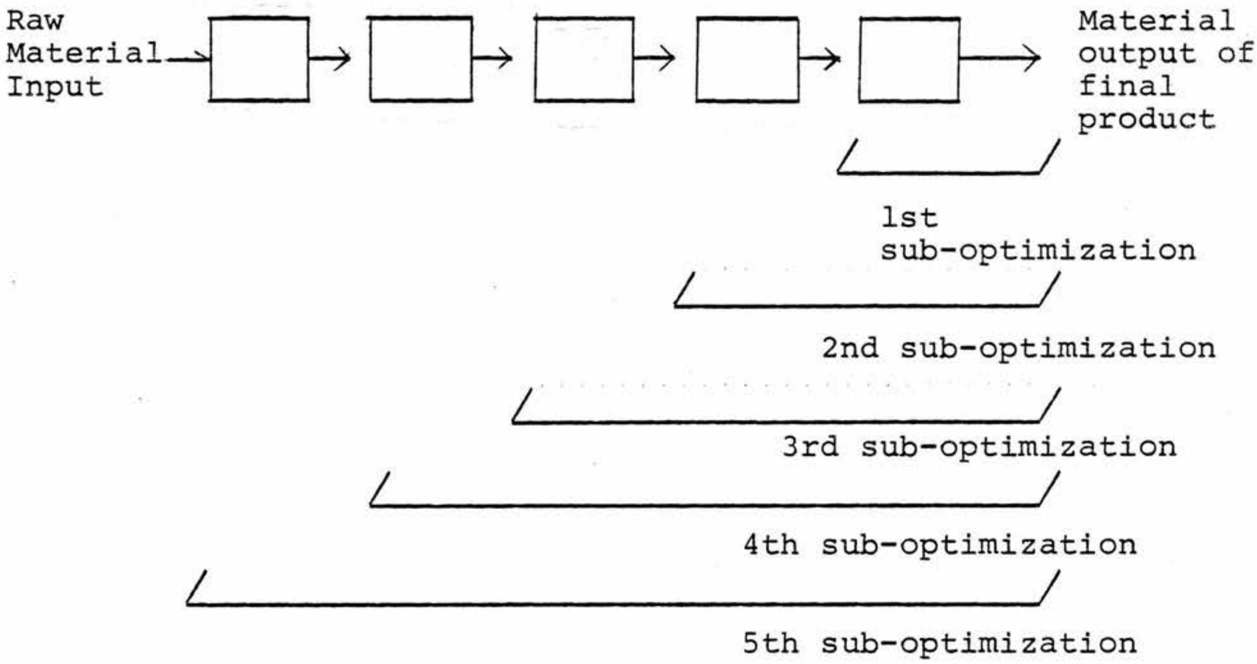
$$f_1(S_1) = \max \left[h(S_1, D_1)\right]$$

$$\text{Subject to } S_n = T_{Dn}(S_{n-1}) .$$

With the direct method, $f_1(S_1)$ is found first to be substituted in $f_2(S_2)$ and so on up to $f_N(S_N)$.

For manufacturing processes it is generally considered more appropriate to work backwards in relation to the material flow, to allow the analytical structure to be more compatible with the flow of design information, which is usually the reverse of the material flow. Thus for each sub-optimization (see below) the optimal value can be computed with respect to <u>all</u> input states to that stage, so that the appropriate alternative can be chosen on this basis. The importance of the backward formulation for sensitivity analysis in relation to input states is discussed further in Section 4.4.

The optimization procedure for directed stages may be illustrated by the following diagram where the arrows indicate the direction of the material flow. Following Rudd and Watson (1968)[1] for a process with 5 stages, 5 "sub-optimizations" may be performed as follows:



The use of the backward formulation has special implications for sensitivity analysis and this is discussed further in Section 4.4. Before this a brief survey is made of the types of structural considerations which have to be taken into account for the application of the D.P. technique. This is done particularly for the class of problems to which the dairy processing problem belongs (e.g. the discrete, deterministic class).

4.3 Problem Formulation for the Application of Dynamic Programming

Unlike Linear Programming which is a specific procedure for solving a special class of problems, Dynamic Programming (D.P.), as mentioned previously, is a technique for handling several different classes of problems. Prior to discussing the algorithms for the solution of a particular class of problems, therefore, the various types of process systems to which D.P. has been applied, are surveyed. This shows the way in which different types of problem structures are formulated for the application of D.P. and puts the dairy processing problem into perspective.

There are certain characteristics of processes which affect the way in which they are formulated for optimization using the D.P. technique. The characteristics relate primarily to the structure of the process in terms of the way the transformation operator functions.

One useful broad classification is that used by Bellman , in which process structures are placed on four levels numbered 0 - 3 and labelled Deterministic, Stochastic, Adaptive and Residual respectively. This classification will be used in this section. Sub-section 1 examines deterministic structures (sequential and non-sequential), while the other three which are less relevant to this study are dealt with in Sub-section 2.

4.3.1 Deterministic Processes

This class of process structure is the one which characterises the type of process to which D.P. is being applied in this thesis. In general, most production processes would fall into this class.

In a deterministic process, an action or decision D in a particular state at stage n (S_n) leads to some new state at the next stage, (S_{n+1}) which can be predicted with certainty, having, therefore, a probability of 1. Thus once the set of decision rules (policy) has been selected, the outcomes are known in advance, as the input state to the next stage (S_{n+1}) is completely determined by S_n and the action decided on (alternative selected) at that stage (D_n).

One feature of a deterministic process, and, in particular, one of the nature of the production process being considered, is that where the process is naturally sequential there is the choice of taking the decisions all together or of treating them singly in stages as is done in D.P. The D.P. technique provides a somewhat more pedestrian approach to a solution but has its advantages in that by exploiting a major characteristic of the process (its naturally sequential, staged nature), the computational difficulties are minimized and its use is invaluable where answers are required not just to a single problem but to a whole class of problems as it is in this case[1]. The relative merits and demerits of the application of D.P. are amplified in Section 4.4.

a. Sequential Deterministic Processes

The D.P. technique has been applied to several optimization problems for naturally sequential deterministic processes,

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1 The optimization procedure is repeated for different economic environments.

many of which have been in the manufacturing sector. These have largely been concerned with i) optimal planning policies (Equipment Replacement; Capacity expansion), ii) Optimal design of processing plants, and iii) Machine or job sequencing.

i) Optimal Planning policies

Two types of optimal planning policies have featured prominently in the D.P. studies relating to the manufacturing sector. These are equipment replacements, and capacity expansion problems.

The equipment replacement problem is usually couched within the framework of a cost minimization problem with the objective being to minimize equipment cost in producing over n time periods from the present, with a cost attached to the decision to keep the old equipment, and a cost attached to replacing it. Bellman and others[1] have paid much attention to the application of D.P. to this type of problem. D.P. has been applied in a similar fashion to the automobile replacement problem with reference to infinite horizon problems.[2]

Capacity expansion problems have been formulated for D.P., within the realm of deterministic processes, by making certain assumptions in order to allow the transformation of states to be deterministic. D.J. White[3] has done this by assuming demand to increase exponentially with time (e^{kt}). The objective is to minimize the costs of meeting demand

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1. These include Bellman (1955), Bellman & Dreyfus (1962) and Bellman & Kalaba (1965).

2 See M.J. Beckmann (1968, p. 26).

3 See D.J. White (1969, p. 56).

over some time period.

In these problems the decision process is of the "yes-no" (stop-go) type. In problems involving process designs the decision structure is more complex. The dairy processing problem is closer to the optimal design problems.

ii) Optimal Design problems

Much of the work done in the area of process systems design has been in the field of Chemical Engineering, and has often been concerned with optimal conversion ratios as a product is passed through a series of conversion operations. There is usually an economic criterion function and this work falls generally within the relatively new field of Engineering Economies.

Several references[1] have been made to the chemical Engineering design problem studied by Mitten and Newhauser (1963), in which they used a D.P. approach to optimize an economic objective function (profit maximization over a 5 year period). The strategy in this case as in many such cases, is to select the design variable (s) at each stage which significantly affects production costs at that stage and to optimize recursively with respect to these design variables.

The study which considered the production of a chemical which goes through a mixing and a heating stage, two reaction stages and a separation stage, the main difference

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1 Among them are G.C. Wells (1973, p. 130); Peters & Timmerhaus (1968, p. 735); Rudd & Watson (1968, p. 229); G.L. Newhauser (1966); O. Converse (1970, p. 160).

between this class of sequential deterministic problems and those discussed before (see i) above) is that, in this case, the decision(s) to be made at any stage differs from those at other stages. For example, at the heating stage the decision variable is the temperature to be used, and the individual stage cost is a function of this temperature and the input state from the mixing stage. At the mixing stage cost is related to the decisions on type of mixer and the mixing efficiency. It is structurally similar to problems found in dairy processing and the problem is worked through and presented as Appendix 7.1.

Other writers have concentrated on optimizing with regard to a particular physical quantity which is considered to have the greatest influence on cost of conversion of the product. Happel and Jordan[1] in optimizing the design of a three-stage gas compressor, seek to optimize the work[2] requirement. Since the cost of compression depends on the power or energy requirements (work), minimizing work equals minimizing cost, with the decision variables being the intermediate pressures.

D.P. Aris[3] has studied the application of the Dynamic Programming technique to the optimal design of chemical reactors, which involves considerations of design variables similar to those discussed already in this section, with sequential conversion operations. Aris has, however, examined more than one type of objective function which could form

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1 See Happel & Jordan (1975, p. 206)

2 This relates to the energy consumption of the process.

3 See D.P. Aris (1961, Chap. 4).

the basis for optimization, listing them as: Stoichiometric[1] objective functions; Material objective functions and Objective functions with operating costs. The objective function could be constructed as some measure of profit to be maximized, or of cost to be minimized.

The studies in this area of naturally sequential deterministic processes have been examined in some detail, because of the similarity between the nature of the process structure involved in these problems and that involved in the dairy processing technology optimization problem that is the central part of this thesis.

iii) Job Sequencing

Another type of problem in the manufacturing sector considered under sequential deterministic processes, is that of the sequencing machine operations in a production plant. The problem is one of performing a set of jobs on a given number of machines with each job, respectively, going in a directed sequence of operations from one machine to the other. The objective is to find the sequence that will minimize the overall time to complete the job (i.e. how to order the jobs to minimize waiting time or idle time for the machines).

The procedure for structuring this problem for the application of D.P. is discussed in detail in Bellman, R. (1951) and in White, D.P. (1969).

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1 Concerned only with changes in the concentration of the species in the feed and product streams.

b. Non-Sequential Deterministic processes

There are some activities which, though not naturally sequential, have still been formulated for application of the staged optimization procedure used in D.P. This, of course, is worthwhile only where D.P. is found to have advantages over the standard calculus approach, and this has been found to be true in several cases. Bellman and Dreyfus, among others,[1] illustrate some of the difficulties involved in the traditional calculus approach to one class of non-sequential process - the allocation problem.

The non-sequential deterministic processes are basically allocation and assortment problems, with rather a different structure from those discussed under (a) above. The way in which the problem must be formulated to be handled by D.P. is therefore different.

The allocation problem is usually illustrated as a barge-loading problem or knapsack problem and is the type of problem involved in trying to allocate a research budget among alternative projects.

Assortment problems are concerned, for example, with the optional combination of sizes of a product to minimize the cost of satisfying the customers' demands for different sizes (known) without producing too wide a variety. D.J. White[2] has done work in this field.

Some ingenuity is required to convert a non-sequential process into a sequential deterministic process for the

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1 See Bellman & Dreyfus (1962, pp. 3-13); D.J. White (1969, p. 38), J.M. Norman (1975, pp. 23-24).

2 See D.J. White (1969, p. 44).

application of the recursive optimization procedures of D.P. These examples indicate the effect of the structure of the process on the way the problem has to be formulated for the use of the D.P. technique using an appropriate algorithm.

4.3.2 Other Process structures

a) Stochastic (or probabilistic) processes - Level 1

In a stochastic process, the transformed state resulting from a decision at the current stage is not known in advance with certainty, as in the deterministic (or level 0) process. In this case only the probability distribution of the occurrence of any transformed state is known. In addition, the payoff or path value at the various stages is not known with certainty and only the expected value can be computed.

For a stochastic process a sequence of optimal decisions is one which maximizes (or minimizes) the expected return (penalty) over n stages (time periods) given the present state of the system.

In general, then, for the stochastic process, the transformation relationship may be written as

$$S_n \quad = \quad T_{D_{n-1}} (S_{n-1}, r_{n-1})$$

where r_{n-1} is an independent random variable with a known probability distribution d G(r).

The aim is to maximize the expected value of the return function. The return R for an additive function may be expressed as

$$R \quad = \quad \exp h\left[(S_1, D_1) + h(S_1, D_2) + \ldots + h(S_N, D_N)\right]$$

using "exp_r" to indicate that the expected value is to be taken with respect to the random variables $r_1, r_2, \ldots, r_n$.

Much of the work on the application of D.P. to stochastic processes has been related to the Markov process. The Markov chain process has a transition structure similar to that of D.P., in which the transition probabilities depend only on the current state of the process and not explicitly on past history. Ronald Howard (1960) devotes a whole book to the study of Markov processes and Dynamic Programming, and several others, including Bellman and Dreyfus (1962) have paid much attention to the subject. In Economic decision making, Martin Beckmann (1968)[1] examined the way in which D.P. can be applied to economic problems involving risk.

Much of the work in the application of D.P. to stochastic processes, has been done in the areas of Operations Research and generally within the field of business studies. The problems of Inventory Control and production smoothing have received much attention, notably from Harvey Warner (1969) and others[2].

b) <u>Adaptive Processes - Level 2</u>

There are some processes in which the degree of uncertainty is even greater than in the case of the stochastic process. With adaptive processes it is considered that even the probability distribution is unknown. However, in general it is supposed that the analytic structure is known although

1 Martin Backmann (1968, p. 37-61).

2 See also D. Bertsekas (1976) and M. Beckmann (1968).

certain parameters are unknown. The process is considered adaptive in that more is learnt about the structure of the process as times goes on.

As with the stochastic approach, the aim is to maximize (or minimize) the expected value of the return or criterion function expressed additively as

$$R = h(S_1,D_1,r_1) + h(S_2,D_2,r_2) + \ldots + h(S_N,D_N,r_N).$$

When a decision is made at the first stage (D_1) the transformation is

$$S_2 = T_{D_1} (S_1,r_1)$$

and the <u>a priori</u> estimate of the unknown distribution is altered depending on the old distribution function, $d\,G(r)$, the observed value of r_1, the initial state S_1, the new state S_2 and the stage 1 decision D_1.

c) <u>Processes of the Residual Category - Level 3</u>

This is Bellman's "catch all" category for systems with transformation processes which do not fit any of the other categories. Among these is the process in which the probability distributions change from time to time in an unknown manner. Bellman uses a sequential game type approach in a similar case, where he assumed that the successive states are chosen by an adversary.

In general, these processes are characterised by gross uncertainty about the structure of the transformation process and the lack of avenues for learning more about the probability of the structure attaining any particular form.

The examples provided in this section give some indication of the wide variety of processes which can be handled using the D.P. technique. The dairy processing problem belongs structurally to the deterministic class (level 0) discussed in 4.3.1. The problem is therefore formulated in a manner similar to that for naturally sequential processes such as the optimal design problem discussed in 4.3.1 (a).

In the following section the special advantages of the use of the D.P. technique for this type of problem, and the disadvantages associated with its use are given some consideration.

4.4 The Merits and Demerits of the D.P. Approach

There are special advantages to be derived from use of the D.P. approach to plant level optimization for a manufacturing process. There are, however, some drawbacks to the use of the technique. In this section the attractiveness of D.P. is considered first and then the limitations are examined.

4.4.1 The attractiveness of the D.P. approach

The D.P. approach is particularly attractive because, as a staged optimization procedure it is capable of exploiting this structural feature of a manufacturing process which is naturally staged. One special advantage is the facility of the technique in handling a large number of variables and constraints when compared to classical optimization.methods, and this has already been discussed in Section 4.1. The other advantages, to be discussed here, relate to:

a) the economy of the computations in comparison with an exhaustive search of all the alternatives which could be evaluated and

b) the way in which the formulation can allow for a built in sensitivity analysis.

a) <u>The computational efficiency of dynamic programming</u>

Where the data type is such that the solution appears to require an exhaustive calculation of all the possible combinations, the number of evaluations of the objective function would increase exponentially with the number of stages. With D.P. the evaluations increase only multiplicatively with the number of stages, giving a substantial reduction in the work load involved and bringing the computer time required within realistically managable proportions.

If, for example, a process has N stages with m components of the decision vector at each stage then the alternatives would number Nm, with a single state at each stage. If, however, there were ten components of the state vector at each stage, then the number of calculations of the objective function required would be 10^{Nm}. In addition, if there are i different initial states for which the problem must be worked, then for each value of the state vector at each stage (assuming one per stage), the optimal values computed would have to take the i initial states into account. Thus there would be 10^{i} considerations of initial states to be added as well. Thus an evaluation of all the possibilities would require 10^{Nm+i} computations.

On the other hand, with the staged D.P. procedure, each stage would require the same number of calculations 10^m for each of the initial states (i) to be considered. Thus there would be 10^{m+i} calculations at each stage giving a total of $N10^{m+i}$ computations.

The ratio $N10^{m+i}/10^{Nm+i}$ may be taken as the measure of the relative efficiency of D.P. over exhaustive evaluation methods. If there are 5 stages each with 10 values of each state variable to be considered, 2 different initial states (i), and 5 components of the decision vector at each stage, then the number of computations required by exhaustive search would be $10^{5\times5+2} = 10^{27}$. The staged D.P. method would, for the same problem, require only $5 \times 10^{5+2} = 5 \times 10^7$ computations, a substantial reduction in computer time and cost, which may, for large and complex problems only just bring the problem within the range of computing feasibility, even with the high-speed digital computing facilities now available.

It may be noted, however, that when i, the number of initial states, increases above 2 (i.e. at least 2 state vectors at each stage) then even with D.P., problems arise with respect to storage space in the computer and the problem can become quite unmanageable. As this is particularly relevant to the type of process being considered in this thesis, this aspect of D.P. is examined in a bit more detail in the discussion of limitations of D.P. (Section 4.4.2).

b) D.P. and Sensitivity Analysis

Another advantage of the D.P. optimization procedure for the discrete deterministic process such as the one under consideration, relates to the way in which the problem can be formulated to provide a built-in sensitivity analysis, without having to resolve the problem.

The D.P. procedure of embedding the original problem into a larger space containing the state variables, and the nature of the staged optimization procedure means that optimal return and optimal decisions are known for all values of the state variables. Thus, using an asterisk to indicate optimal values, when $f_N^*(S_N)$ (the optimal value of the return function at the final stage to be optimized) is determined, then the optimal decisions are known for every state variable $(D_N^*(S_N), \ldots, D_1^*(S_1))$ and, furthermore, for every component of the state vector $[\bar{S}_N = (s_{1n}, s_{2n}, \ldots, s_{rn})]$ of the state variable at every stage. Thus it is possible also to identify the optimal input state for each stage.

Because of this feature of the D.P. optimization technique, it becomes possible to analyse how sensitive the returns are to particular input states. The decision to use a recursive relationship that moves backwards in relation to the time sequence of the process, or one which moves forward is very usually made with respect to the desirability of having a basis for a particular type of sensitivity analysis.

If the D.P. process is carried out by working backwards in time (i.e. starting at the last stage of the process, in time) then the last input state vector to be considered is the initial input state vector to the process. When the backtracking procedure is done, the optimal policy is contracted forward from the first stage in time. Since the optimal values are known for all initial states, then, in addition to selecting the global optimum value of the return function (identifying S^*_{ri}) and contracting forward from this value alone, it is possible, without recomputing the problem, to compare the values associated with other states with the optimal value. This way it is possible to measure the effect on the optimal value, of the variation in initial input state values and to identify second and third best policies.

If, however, it is the final state vector that is the object of the sensitivity analysis, then the forward recursion would be used, so that when the backtracking is done, the optimal policy is contracted backwards (i.e. from the last stage in time) so that the sensitivity of the value of the return function to the various components of the final stage state vector can be analysed.

In addition, the D.P. procedure can provide a sensitivity analysis with respect to the number of stages N. Because of the recursive nature of the programming calculations, information on the way in which the optimal return (costs) varies as a function of the number of stages, is obtained in the course of the optimization procedure.

Although this latter type of sensitivity analysis may be more relevant to process where the number of states cannot be described as finite, known (e.g. optimal path, allocation processes etc.), it may still be of some value in a finite stage process such as is being considered here. The sensitivity analysis in the number of stages (N) may be combined with the sensitivity analysis on initial or final state values to give a more complete analytical description of the optimal system behaviour.

4.4.2 The Limitations of Dynamic Programming

The criticisms of the D.P. technique are made largely on two grounds:

a) that it performs too many calculations, and

b) that it is plagued by "the curse of dimensionality".

These criticisms are examined in greater detail, to assess their relevance to the type of problem being considered.

a) The Redundancy of the Calculations

In Section 4.4.1, it was shown how the D.P. method of staged optimization performed fewer calculations than an exhaustive evaluation of all possible combinations of states and decision would require. Nevertheless, it is often felt that D.P. still performs too many redundant calculations.

This is mainly because values are computed for all input states (components) for all decisions at each stage. Finally, in backtracking to find the optimal overall policy, only one value of each input state vector and one value of the decision vector is relevant at each stage in describing the optimal path through the system.

This criticism would acquire some validity in terms of an optimal path or allocation type of problem where the aim is simply to determine the single path through the maze that optimizes the return function. For some such problems, however, the nature of the difficulties encountered in applying alternative methods of optimization, while not invalidating the criticism, certainly makes it less meaningful and relevant.

For the naturally sequential, deterministic, staged process which is being considered here, this may, in fact, be a non-criticism in the light of the preceding discussion on sensitivity analysis. These extra values relating to states and decisions not on the optimal contracted path, can be useful for sensitivity analyses.

b) The "Curse of Dimensionality"

Ideally for D.P., there thould be only one state parameter at each stage of the process. In this case the dimensionality (i) = 1. Where there are two or more stage parameters at each stage, one of the greatest limitations of D.P. is encountered. This is the dimensionality restriction. Computer time and storage space requirements increase, since, as stated in 4.4.1, the number of computations required increase exponentially with i. Thus dimensionality is considered a curse.

It is generally agreed that when the dimension rises above two the computations involved can assume such great proportions that they may exceed the capabilities of even the most advanced, high speed digital computers, or, at least, require so much time and storage space as to render the technique particularly burdensome and unwieldy and expensive.

Since this dimensionality is often viewed as one of the biggest stumbling blocks in the widespread use of D.P., a great deal of effort has been expended in trying to find ways to overcome the dimensionality problem. In the case of continuous functions, one of Bellman's suggestions is to resort to polynomial approximation[1]. This is less applicable in this discrete case. However, two other suggestions may be examined, these are a) the use of Lagrange multipliers and b) the reduction in grid size.

a) <u>The use of Lagrange Multipliers</u>

Lagrange Multipliers may be used to reduce the number of dimensions by one. The trick is to use, say, one dimension and to relate the components of this state vector to each of those of the second state vector by some value λ (the Lagrange multiplier) which is then weighted in some agreed way in relation to the components of the included state vector. After the values have been arrived at for the one- (or one less-) dimension problem, the value of λ can be varied to derive the new values of the function when this other dimension is taken into account.

It must be noted, however, that it cannot be taken for granted that, in the variations of λ, <u>the</u> optimal solution will be found - it may be possible to miss the optimal solution. This feature tends to limit the power of the Lagrange multipliers in reducing the burden of dimensionality.

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1 <u>Loc</u>. <u>cit</u>.

b) Reducing grid size

Whereas the purpose of introducing Lagrange multipliers is to reduce the computations - by reducing the number of variables at each stage (state vectors) by one, this alternative method seeks to reduce the computations by considering fewer values (components) in each state vector.

Using this method, it may therefore be possible to include the extra dimension without placing undue stress on the computational facilities.

These techniques may be applied jointly to any problem to moderate the effort involved in finding an optimal solution.

In general, however, in the problem of optimizing at a plant level and taking into account the inter-relationship between sub-processes or groups of processing operations, the use of the D.P. technique seems to have distinct advantages which tend to outweigh the disadvantages.

In order to determine the nature of the technological decisions which could be made at each stage in a dairy processing plant and to understand the nature of the transition relationships, the underlying engineering principles must be studied. The following chapter discusses the basic fundamentals of process engineering which have been applied in this thesis.

CHAPTER 5

THE ENGINEERING BASIS FOR DAIRY PROCESSING PRODUCTION FUNCTIONS

The production function in Economic Theory is an expression of a physical relationship between factor inputs and outputs. In order to expose this physical relationship, which usually appears wrapped up in a bundle of monetary values, some familiarity with the relevant engineering fundamentals is required. This knowledge makes it easier to quantify the physical variable and to translate these into the more familiar economic factors. In doing this any set of factor price ratios appropriate to any particular economic environment can be applied.

Given that the purpose of the research is not to re-design equipment or to restructure processes, the knowledge of basic engineering principles required is not extensive. It is, however, vital to the process of preparing a sound basis for the type of comparative analysis an economist would want to make in relation to "appropriate" technology.

In a detailed technological analysis of this nature, a great deal of assistance from equipment manufacturers and suppliers is necessary to provide much of the basic data on the existing equipment systems. Much of these data, however, must then be converted into a form from which the relevant variables required for the economic evaluation of alternatives, can be derived.

In providing a basis for the quantification of the physical factor components of the technological alternatives, this chapter contains an explanation of the engineering fundamentals pertinent to the particular type of processes found in the dairy plant. The principles, explained in some detail, are those which have been applied in arriving at some of the physical factor quantities which are used in the later analysis.

The first section examines heat transfer, fluid flow and other engineering principles that have been used in deriving some of the physical factors. The second section discusses the physical factors and their computation with reference to some of the principles described in the previous section.

The nature of the problems involved in trying to extract the necessary basic data from equipment manufacturers and suppliers, and from processors, is detailed in the final section.

5.1 Process Plant Engineering Principles

The engineering principles useful to a study of Dairy Processing are related broadly to those involved in a) Heat transfer (preservation operations), b) Fluid flow, c) Mass Transfer (conversion operations) and d) Power transmission. These provide valuable data on energy consumption, a variable largely ignored in economic analyses when alternative processes and equipment systems are being compared, but which can be of vital importance, especially in an era of high energy costs.

5.1.1 Heat transfer principles

A large part of the processing operations for the production of dairy and other food products, and of pasteurized milk in particular, is concerned with preservation operations which are primarily heat transfer operations (heating, cooling). Much of the equipment used therefore, is of the heat-exchanger type and so some familiarity with the principles involved in heat exchange is necessary so that engineering variables (heat, etc.) to "physical" or intermediate variables (e.g. fuel, kilowatt hrs, etc.) to which costs can be attached.

Heat may be defined as "... a form of energy which will flow with or out of a body when a temperature difference exists between the body and its surroundings."[1] Heat flows from high- to low-temperature bodies. Thus in thermodynamics and heat-transfer relationships, temperature is an important parameter. The major areas of interest here concern a) the quantification of heat, b) the nature of the heat transfer process and c) the principles of energy conversion.

a) The Quantification of Heat

Heat is usually measured either in British Thermal Units (Btu) or in calories (cal). In this study the Btu will consistently be used as the unit of heat.

One Btu is the heat required to change 1 lb. of water at 64^{o}F by a temperature of 1^{o}F. The Btu requirements of a product for changing its temperature depends on what is referred to as the specific heat of the product. This specific heat is a measure of the quantity of heat units

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1 See A.W. Farrall (1963, Chapter 6).

(Btu) required to change the temperature of 1 lb. of product, either by heating or cooling, without change of state. A specific heat of one (1) for a product indicates that it requires 1 Btu to change 1 lb of it by a temperature of $1^{o}F$. If it requires less than 1 BTU, then the specific heat is less than one (1). The specific heat of milk with 3.5% butter fat is given as 0.93, which is higher than for cream (e.g. cream at 60% butter fat - specific heat = 0.75) and lower than for skim milk (0.95)[1]. The specific heat of water is 1.00.

Knowledge of the specific heat of a product is unimportant because it is useful in computing the number of Btu required to carry out a specific heating process and this Btu figure can then be converted to other forms of energy depending on the energy source used. The quantity of heat, Btu, required to change the temperature of a product is represented as

$$Q = S_a(w)(\Delta t)$$

where Q = No. of Btu required

w = weight in lbs.

Δt = temperature change in Fahrenheit

S_a = apparent specific heat

For example, if it were necessary to find the amount of heat required to pasteurize 10,000 lbs. of milk, knowing that the milk enters at $45^{o}F$ and leaves at $145^{o}F$, and that the overall heat efficiency of the pasteurizer is 85 percent,

1 From Harper & Hall (1976, p. 431).

the solution could be found by applying the formula:

$$Q = \frac{S_a(w)(\Delta t) \times 100}{\%\ \text{efficiency of heat exchanger}}$$

Thus $$Q = \frac{0.93 \times 10{,}000 \times (145 - 45) \times 100}{85}$$

$$Q = 1{,}094{,}100 \text{ Btu}$$

where the apparent specific heat of milk is 0.93.

The term "apparent" specific heat is used because the heat considered is not only the "sensible" heat, or the heat associated with the change in temperature (such as can be measured with a thermometer), but also includes the "latent" heat or the heat which is associated with a change in the state of the product rather than a change in temperature.[1]

Once the Btu required for the temperature change is known, this can be converted into other energy units. For example, 3,412 Btu is the heat equivalent of one kilowatt hour (Kwh) of electricity, where the watt is the measure of electrical power (watts = volts × amperes for direct current) and a kilowatt hour is 1,000 watts flowing for one hour. The Kwh is the standard unit for the measurement of electricity consumption and for the calculation of electrical energy costs.

The Btu is also convertible to horsepower hours, where 2,545 Btu is equal to one horsepower-hour (one horsepower in use for one hour). The horsepower is the unit generally used with motors and heavy equipment. Motor costs are in

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1 e.g. when any steam condenses to form water a quantity of heat is given up without a change in temperature.

general related to motor horsepower.

Where the Btu cannot be measured directly, it can be measured indirectly by using temperature difference between two locations which represents the "driving force" for the movement of heat (remembering that heat moves in a direction from hot to cold).

b) The nature of the heat transfer process

Heat is transferred by conduction, convection or by radiation, all of which may be used together in a particular equipment system.

i) Heat transfer by conduction

Conduction refers to the transfer of heat through a fixed material. This is demonstrated in a pasteurizer vat where, with one side of the lining heated, the other side becomes hot also. As expected the extent of the conduction of heat from one side of the material to the other depends on the thermal conductivity of the particular material, or the ability of the material to pass heat through it. There are tables available which give the thermal conductivity of selected materials.[1] Once this is known, the rate of heat transfer, q, expressed as Btu per hour is derived from the following formula[2],

$$q = \frac{k}{x} A_m(\Delta t)$$

where,

k = the thermal conductivity of the substance expressed in Btu per hr sq. ft. Fahrenheit per foot.

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1 See Harper & Hall (1976, p. 452).

2 This equation relates to steady state heat transfer where the rate of heat transfer remains constant and is unaffected by time. Unsteady state heat transfer equations are more complicated.

x = the material thickness or length of the heat transfer path expressed in ft. or the same units as k. (inches more appropriate for structural materials).

A_m = the mean area perpendicular to the direction of heat transfer in square feet.

Δt = the temperature difference along the path of heat transfer, ^oF (driving force).

Special formulae are available for calculating A_m for different wall shapes (e.g. cylindrical or spherical) through which the heat passes. For a sphere, the area represented by the geometric mean is used

$$A_m = (A_o A_i)^{\frac{1}{2}}$$

where A_o = outside area, and

A_i = inside area.

From this information the efficiency of the heat exchanger can be estimated to compute the energy requirements for the job.

ii) Heat transfer by convection

In convection transfer, the heat is transferred by the physical mixing of the hot and cold portions of a fluid. In what is referred to as "natural" convection, the mixing takes place as a result of temperature induced density difference, whereas "forced" convection occurs as a result of mechanically induced agitation. In a pasteurizer vat mechanical agitators are generally used to assist the convection process inside the tank after the heat is transferred by conduction through the shell.

For evaluating rates of heat transfer by convection the following equation is used:

$$q = h\ A\ \Delta t$$

where h is the heat transfer coefficient which is analogous ro k/x in the equation for heating by conduction and is sometimes referred to as the film coefficient or surface thermal conductance in Btu per hr. sq. ft. Fahrenheit. h is a function of the agitation and the nature of the fluid.

A = the cross sectional area in square feet and

Δt = the temperature difference between the bulk of the fluid and the surface of the material through which the heat is being passed, Fahrenheit.

Usually the heat is transferred jointly by convection and conduction (and sometimes by radiation as well), thus in heat transfer calculations it is customary to use the overall heat transfer coefficient, U, in place of h, which is similarly expressed in Btu per hr. sq. ft. F. The value of U can therefore be used to relate the area of heat exchange surface and the rate of heat transfer. The temperature difference involved is deduced from knowledge of the heat to be transferred and the types of fluids on each side of the heat-transfer surfaces.

The U value may be determined once the inside and outside film coefficients are known, along with the fouling coefficient[1]. Some values of U have been worked out and are accessible in relation to specific types of heat exchangers and the substances on either side. For example, in a coil vat (e.g. pasteurizer) with a revolving coil in the milk, the value

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1 A factor to compensate for the additional resistance to the flow of heat caused by the dirt or scale which forms on the heat transfer surfaces.

of U is given in Btu per hr. sq. ft. F as 200. Further interesting values which relate to some of the equipment being studied are presented in Table 5.1.

For a particular application, the U values may be used in the equation,

$$q \quad = \quad U \; A \; \Delta t \text{ Btu/hr.}$$

The manufacturer often provides information on the heat-exchanger surface. The temperature difference or driving force, Δt, is represented by the log mean temperature,

TABLE 5.1

Some Approximate Overall Heat-Transfer Coefficients (U).

	Btu per hr.Sq.ft. F
Steam boiler	2 - 15
Surface steam condenser	200 - 1000
Water heaters	200 - 1500
Shell and tube ammonia and freon condensers	150 - 300
Shell " " water cooler	15 - 20
Shell " " brine units	90 - 100
Shell " " steam heater for water	100 - 300
Surface cooler, milk to water	175
Coil vat, revolving coil (milk)	200

Source: Extract from Harper, W.J. and Carl W. Hall, Dairy Technology and Engineering, Westport Conn. AUl Pub. Co. (1976, p. 458).

Δt_m with

$$\Delta t_m = \frac{Gtd - Ltd}{\ell n \frac{Gtd}{Ltd}}$$

where

Gtd	=	the greatest temperature difference of the ends of the heat exchange and
Ltd	=	the least temperature difference at the ends of the heat exchanger.

This equation holds for all of the three main types of flow heat exchangers (as in HTST pasteurizers, coolers, etc.), characterised by parallel flow, counter flow and cross mixed flow, with a heat exchanger between the fluids.

With this knowledge, the Btu per hour (q) for a particular application can be derived and the Btu value subsequently converted into electrical energy or fossil fuel requirements as desired (see Section iii) below).

iii) <u>Heat transfer by radiation</u>

This is the third type of heat transfer which may occur in conjunction with one or both of the others above. In this case radiant heat energy is transferred from a source body to a receiving body. The receiving body then re-radiates energy at a lower temperature, absorbing some of it. The interest is usually in the net rate of heat interchange between the two (or more) bodies.

The equation for radiant heat transfer includes a variable ε, the value of which depends on the characteristics of the emitting surface, and which is referred to as the emissivity of the material. Values for ε, in relation to specific materials are available.[1]

The rate at which radiant heat energy is emitted from a source is given as

$$q = \sigma \varepsilon A T^4$$

where, as usual q = the rate of heat transfer, in Btu per hour, and

σ = a constant known as the Stefan-Boltzmann constant with a value equal to 0.1713×10^{-8} Btu per hr. sq. ft. in ^{o}R [2]

ε = emissivity of the surface

A = exposed-surface area of heat transfer, sq. ft.

T = absolute temperature in ^{o}R

where the net heat transfer between two bodies 1 and 2 is required and it can be assumed that the emissivity of the body is the same as its adsorptivity (ability to absorb heat energy). The rate of heat transfer q in Btu per hour is

$$q = \sigma A \varepsilon (T_1{}^4 - T_2{}^4)$$

or

$$= 0.173 A \varepsilon \left[\frac{(T_1)^4}{100} \quad \frac{(T_2)^4}{100}\right]$$

In order to add the heat transfer of radiation to that of conduction and convection to get the overall heat-transfer coefficient U, a value of h for the heat-transfer coefficient of radiation h_r is computed, where

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1 See Harper & Hall (1976, p. 461) and Peters & Timmerhaus (1968, p. 533).

2 ^{o}R - the British system of measuring absolute temperature is in degrees Rankine = $^{o}F + 460$.

$$h_r = \frac{0.173\ \varepsilon\ \left[(0.01\ T_1)^4 - (0.01\ T\ )^4\right]}{T_1 - T_2}$$

The U values then relate to all the heat transfer coefficients together for heat transfer by conduction, convection and by radiation.

c) Energy conversions

The heat transferred to the product by any of the means described above must come from a primary heat source such as a boiler or electric element using a heating medium such as steam or hot water. Refrigeration using, say, brine or ammonia as the heating medium is, of course, also a heat transfer operation.

It is important therefore to be able to convert the Btu required for the particular operation into electrical energy or boiler Hp for steam generation, so that energy costs may be derived and also so that the size (capacity) of the heating source may be computed to determine capital costs.

For conversion to electrical energy, it has already been mentioned that 1 kilowatt hr = 3,412 Btu (see Section i) above). In most cases, however, the heat transfer medium for heating the plant is steam. Hot water is less popular because less transferrable heat is carried per unit mass. Both media, however, will be considered in discussing the conversion of the heat in Btu required by the product to energy required at the primary energy source for heating. The second part of the discussion relates to energy for cooling.

i) Energy requirements for heating the product

Steam, used as a heating medium is usually produced within the plant in a boiler or steam generator, and the steam is used to carry heat from a fuel to the product. Steam is vaporized water which is formed by adding heat to water.

More heat is carried per pound in steam than in water. One pound (lb.) of water at 32°F (zero heat) heated to 212°F, carries 180 Btu of sensible heat (approx. 1 Btu for each pound (lb.) of water, for each 1°F increase in temperature). At a pressure of 0 psig[1] an extra 970 Btu of latent heat (of vaporization) can be added to convert the water into steam, giving a total heat to the medium of 1150 Btu.

The total heat (sensible and latent) in Btu contained in the steam for different pressures may be obtained from steam tables generally available in chemical engineering texts.[2] Table 5.2 provides steam data for pressures from 1 to 260 absolute pressure per square inch (psia).

It may be noted that the steam used in a dairy may be classified as wet or dry. Dry steam is formed when all the water is vaporized, that is, when 970 Btu of heat is added to 1 lb. of water at normal atmospheric pressure (0 psig). If any amount less than 970 Btu is added then the steam contains water as droplets or mist as vaporization is incomplete. In addition some processes require superheated steam, which is steam for which the temperature is above that of the

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1 Normal atmospheric pressure at sea level. Pressure can be increased by operating within a vacuum, and is decreased with increasing altitudes above sea level.

2 See Peters & Timmerhaus (1968, p. 827) and Harper & Hall (1976, p. 463).

TABLE 5.2

Thermal Properties of Saturated Steam (Btu/16)

Pressure (Psia)	°F	Sensible heat	Latent heat	Total heat	Vapour (cu ft/lb)
1	102	70	1036	1106	334
6	162	130	1001	1131	74
10	193	161	982	1143	38
14.7	212	180	970	1150	27
20	228	196	960	1156	20
30	250	219	945	1164	13.7
40	267	236	934	1170	10.5
50	281	250	924	1174	8.5
60	293	262	916	1178	7.2
70	303	273	908	1181	6.2
80	312	282	901	1183	5.5
90	320	291	894	1185	4.9
100	328	298	889	1187	4.4
120	341	312	878	1190	3.7
140	353	325	868	1193	3.2
160	363	336	859	1195	2.8
180	373	346	851	1197	2.5
200	382	355	843	1198	2.3
220	390	364	836	1200	2.1
240	397	372	829	1201	1.9
160	404	380	822	1202	1.8

Source: A Farall (1963)

dry (saturated) steam at the same pressure. This type of steam, however, is usually used for driving turbines rather than for heat transfer in processing. Steam calculations, in this thesis, are made with respect to dry saturated steam.

Once the steam requirements are known, the boiler horsepower required can be calculated and the amount of fuel required can be determined when the heating value of the primary fuel used in the boiler is known.

Boiler size (capacity) is usually given by the amount of water that can be evaporated (turned into steam) in a given time (usually 1 hr.) under standard conditions, or the rate of heat transfer in Btu per hour. One boiler horsepower (Bhp) is equivalent to 33,470 Btu per hour, or equivalent to evaporating 34.5 lbs. per hour at 212°F (0 psig).

For example, if 2,000 lbs. of water is to be heated from 60 to 160°F in 1 hr., the boiler Hp required can be found from using the formula

$$\text{Bhp} = \frac{S_a \, (w) \Delta t}{33,470} \; .$$

Thus,

$$\text{Bhp} = \frac{1.0 \; (2,000)(100)}{33,470}$$

$$\simeq 6.0 \; .$$

When the amount of steam (in lbs.) required is known, the amount of primary fuel required for use in the boiler to produce this quantity of steam, may be computed from the equation:

$$\text{Pounds of fuel required per pound of steam} = \frac{\{\text{Btu required to evaporate 1 lb. of water at pressure used}\}}{\{\text{Heat value of fuel in Btu per pound} \times \text{boiler efficiency}\}}$$

A boiler efficiency of 70-80% is usually considered for the above equation and the most commonly used fuels are coal, oil and gas. Table 5.3 gives the heat values for several types of fuels.

TABLE 5.3

Heating Value of Typical Fuels

Fuel	High heating value (Btu per lb.)
Coal	11,000 - 14,000
Oil	18,000 - 19,500
Natural gas	700 - 1,800 Btu/cu.ft.
Lignite (dry)	6,000 - 7,000
Bagasse (dry)	8,000 - 9,000
Gasoline	20,200
Kerosene	19,900
Fuel Oil	18,500
Hardwoods	8,100 - 8,900
Softwoods	8,400 -11,000

Source: Harper and Hall (1976, p. 442)

ii) Refrigeration energy requirements

Natural or mechanical methods of refrigeration methods may be used for cooling a product. In natural refrigeration ice is used to absorb heat from the warm product. Each pound (lb.) of ice changed from 32°F solid to liquid at the same temperature takes 144 Btu away.

However, in dairy plants generally mechanical refrigeration is used. In the case of direct refrigeration a compression (or absorption) system is used. A refrigerant such as ammonia, a substance with a low boiling point[1], is passed through a coil which may be referred to as an evaporator, as it is in this coil that the refrigerant boils and vaporizes into a gas. As the refrigerator boils, say at -28^{o}F, it cools down the liquid outside the coils. The heat of the product to be cooled moves from the product to the surrounding air and this air moves by either natural or forced convection to the surface of the evaporator coil. The heat moves through the evaporator coil to the refrigerator.

One feature of most mechanical refrigeration systems is that the refrigerant is reused continuously and thus the actual cost may be negligible. The vapour resulting from boiling is not usually allowed to escape, it is generally forced by a pump or compressor into a condenser where the vapour is cooled by water or air which condenses it back into a liquid to be reused.

A refrigeration system is rated by the rate at which it is capable of extracting heat units, Btu, from the product (i.e. the heat which enters the evaporator), usually expressed in tons. One ton of refrigeration will remove 12,000 Btu per hour.

In the absorption system direct refrigeration, gas, coal, fuel oil, electricity, solar or some other source of energy

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1 Ammonia has a boiling point of -28^{o}F.

is used to provide external energy to move heat from a low temperature space to an external high temperature space.

This direct type of refrigeration is relevant primarily to the storage of the finished product in cold rooms. Of much greater relevance is the type known as indirect refrigeration. Much of the cooling during the processing of pasteurized milk is done by indirect refrigeration systems involving the circulation of cold water or brine.

In the ice-bank indirect system, water is frozen on the evaporator (which has the refrigerant inside), and an ice-bank is built up. Water is then circulated by pumping it around past the ice bank where it is cooled, and it is then circulated through a heat exchanger for cooling the product. The temperature rise of the water during the process is, according to Harper & Hall (1976), 8 - 15^{O}F.

In the brine system, common salt (sodium chloride), calcium chloride, sugar, alcohol, anti-freeze or some organic compound is added to the water to decrease the freezing point of the solution. The solution is circulated in much the same way as in the ice bank system mentioned above.

In the indirect system the thermal efficiency is usually less than in the direct expansion system because one extra heat transfer is necessary. It is of particular advantage, however, in the processing of fluid milk where the milk just needs to be cooled rather than frozen. With circulating cold water the temperature will not go below 32^{O}F, the freezing point of water (or it will turn into ice), and so the product, which will have a freezing point below 32^{O}F, will not freeze.

The energy required can be calculated on the basis of the heat units to be removed at both heat exchange points in the case of the indirect system.

5.1.2 Fluid Flow Principles

The fluid flow processes in the pasteurized milk plant include the pumping of fluid through pipes and over surfaces, the application of centrifugal processes, and homogenization processes. In this connection, some very basic understanding of fluid dynamics is necessary, again, largely to provide some basis for calculation of energy requirements. Much of the attention will be focussed on the pipes and pumping systems with only a brief look at centrifugal separation and homogenization forms of fluid flow, since in the case of the latter the information from manufacturers would largely suffice to indicate their energy consumption levels.

a) Hydraulics and pumping

In some parts of a dairy, it is possible to allow the liquid to flow through pipes under the influence of gravity thereby avoiding the use of mechanical force and the energy required for it. Milk is sometimes discharged from a bulk tanker to the processing plant by gravity flow methods. Inside the plant, a tank may be elevated such that milk flowing from it may do so under the influence of gravity (e.g. from a temporary storage location to a pasteurizer or to a filler).

In other cases, however, a pump is necessary to provide the force necessary to move the product through the pipeline. As the product flows through the pipeline, energy is consumed as a result of the friction between the fluid and the pipe surface. Where the fluid meets the pipe surface, there is no movement (zero velocity) and this velocity increases towards the centre of the tube. The amount of frictional energy consumed is an increasing function of the length of the pipe and the number of bends (or changes of direction) within the pipeline.

A certain quantity of milk per hour must pass through the pipes, fittings and process equipment during production. The product velocity through the pipes will be determined by the size of the passage (i.e. the inside diameter of the pipe). The larger the diameter the slower the product will flow. In selecting the appropriate size pipe (diameter) for a product the flow rate of the product must be known along with the desired velocity.

Figure 5.1 shows the relationship between the diameter and the product velocity.

Now, the faster the flow, the greater the friction in the liquid itself, and between the liquid and the pipe wall, and, consequently, the greater the mechanical bruising of the product. Therefore, for each product, there is an upper limit on velocity that may not be exceeded if quality requirements are to be met. For milk this velocity is given as 5.9 ft. per second (1.8 metres/sec)[1]. A larger size of pipe may be chosen, but the larger pipes mean larger components and increased costs. Thus the diameter nearest to the limit is usually selected. Pipe costs are closely related to pipe diameter.

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1 Alfa Laval Dairy Book (p. 60).

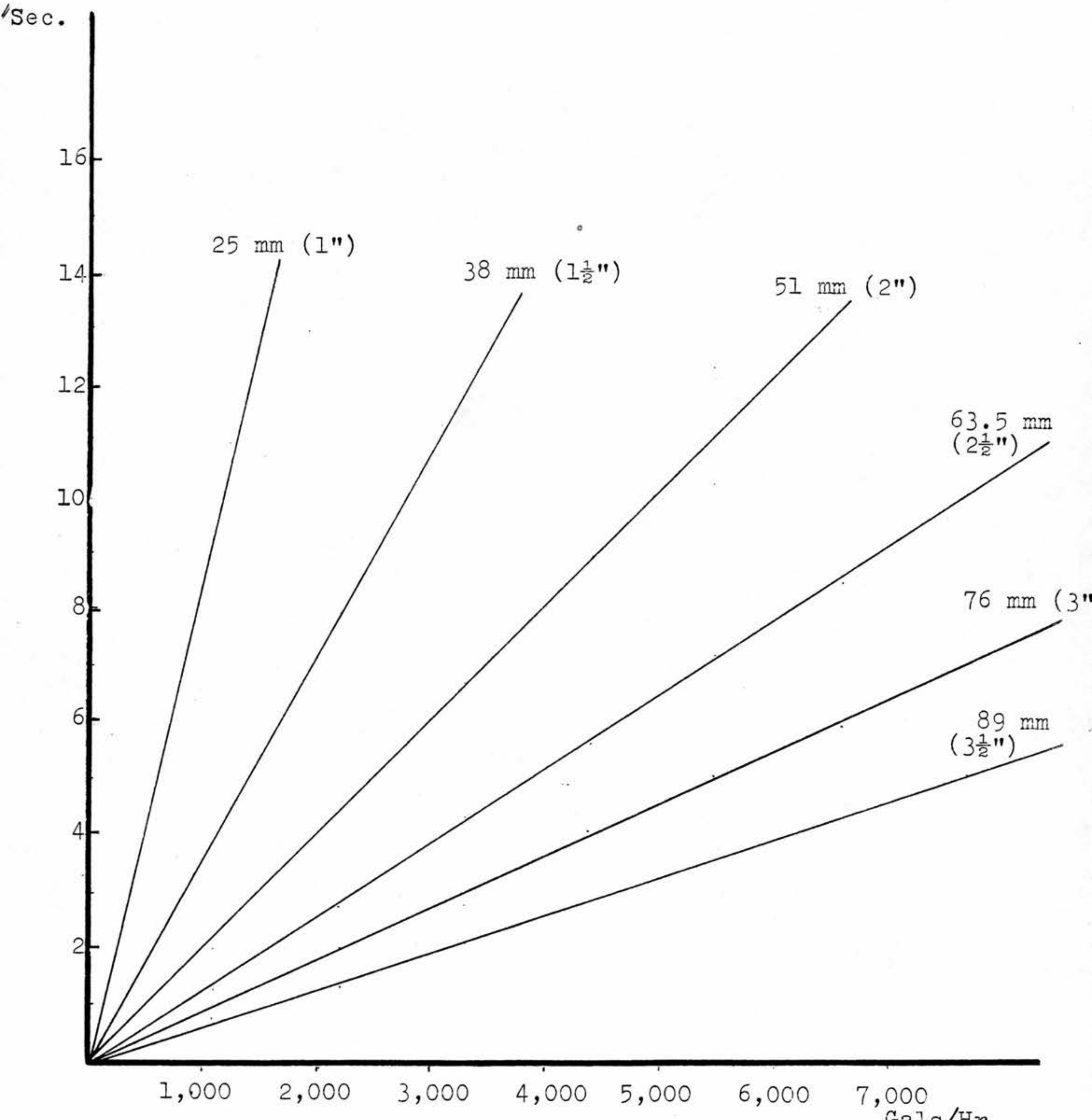

Figure 5.1 Optimum Pipe Diameter.

Source: Alfa Laval Dairy Book.

As the liquid flows through the pipe, the loss in energy is, in hydraulic terminology, referred to in terms of pressure drop measured in pounds per square inch (psi) or feet of fluid flowing (head). The purpose of the pump, therefore, is to provide the required pressure or head.

Data regarding head losses due to friction are given in terms of "feet of head lost per foot" at a specified flow rate (velocity) in psi. Manufacturers, however, tend to give pump performance figures in terms of available discharge head in feet of water at a given flow rate. To convert head losses and pressures in psi to losses and pressures in feet of water, the equation

$$1 \text{ psi} = 2.31 \text{ ft. of water}$$

can be used, indicating that a gauge pressure of 1 psi would support a column of water of 2.31 ft. high. Thus a column of water 46.2 ft. high would exert a pressure of $\frac{46.2}{2.31} = 20.0$ psi.

In order to find the energy required to pump the liquid through the pipe, it is necessary to find the foot-pounds force per unit of time. This is equal to the required head of the pump times the flow in mass per unit of time (lb./min.). Since the energy transfer from the pump to movement in the fluid is not 100%, account must be taken of this inefficiency. Given that 33,000 ft. lb./min. are equivalent to one (1) horsepower (Hp), the horsepower value of a pump motor required for doing a particular job is

$$\text{Hp} = \frac{(\text{Head in ft.})(\text{flow in lbs./min.})}{\text{efficiency} \times 33{,}000}$$

This Hp can be converted to electrical energy units using the equation

$$1 \text{ Hp} = 746 \text{ watts of electrical power.}$$

This would hold true if the conversion of electric power to horsepower were 100% efficient. Some allowance must again be made for this inefficiency.

In order to find the head in ft., all friction losses along the line must be computed for a given flow rate or velocity and to this must be added the minimum pressure at the outlet end converted to feet (of water) as given above. If the flow rate is given in gallons/min (gpm) then the specific gravity[1] must be taken into account in converting to lbs./hr. Using the conversion equation

$$1 \text{ gal/min} = 600\ \rho \text{ lb/hr}$$

where ρ = the specific gravity of the liquid,

then for milk

$$1 \text{ gal/min} = 600\ (1.032) \text{ lb./hr.}$$
$$= 619.2 \text{ lbs./hr.}$$

since the specific gravity of whole milk is 1.032. Manufacturers of dairy equipment do not always give the output in lbs./min. and so this conversion is necessary.

The friction loss along the line in relation to the rate of flow, the size of the pipe and the number of elbows and bends in the piping and this value can be read off from friction loss tables.[2]

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1 Specific gravity (density) is the ratio of the weight of a product to an equal volume of water.

2 See Harper & Hall (1976, p. 395).

These figures can simply be plugged into the horsepower formula given above and the energy requirement can be determined. Manufacturers usually provide data on the efficiency of their pumps in relation to the flow rate of the product. They often also provide data on the power requirement for the pump in relation to the various flow rates, and the corresponding maximum discharge pressure (head) of the pump.

Useful pump information is summarised in Figure 5.2. The flow rate and head are given in gallons per hour and in feet respectively. From the diagram it can be seen that at a flow rate of 5,000 gal./hr., the maximum discharge pressure of the centrifugal pump corresponds to a head (or liquid column) of 70 feet. The power requirement for the pump motor at this flow rate is 3.2 hp. and the efficiency of the pump is 60%. This means that some 40% of the energy from the motor is lost in pumping. This graph provides a quick source of information, avoiding the more detailed calculations that would otherwise have to be made.

b) <u>Centrifugal separation and homogenization</u>

Centrifugal separation is a fluid flow process which, in the pasteurizing plant served two main purposes: to remove foreign matter for clarification of the raw milk, to separate the fat from the skim (non-fat) milk in a separation process for the production of cream and skim, and to standardize milk by removal of fat to adjust the fat content to a desirable level.

The centrifugal separator works on the principle that if a vessel is filled with liquid, the spinning of the vessel

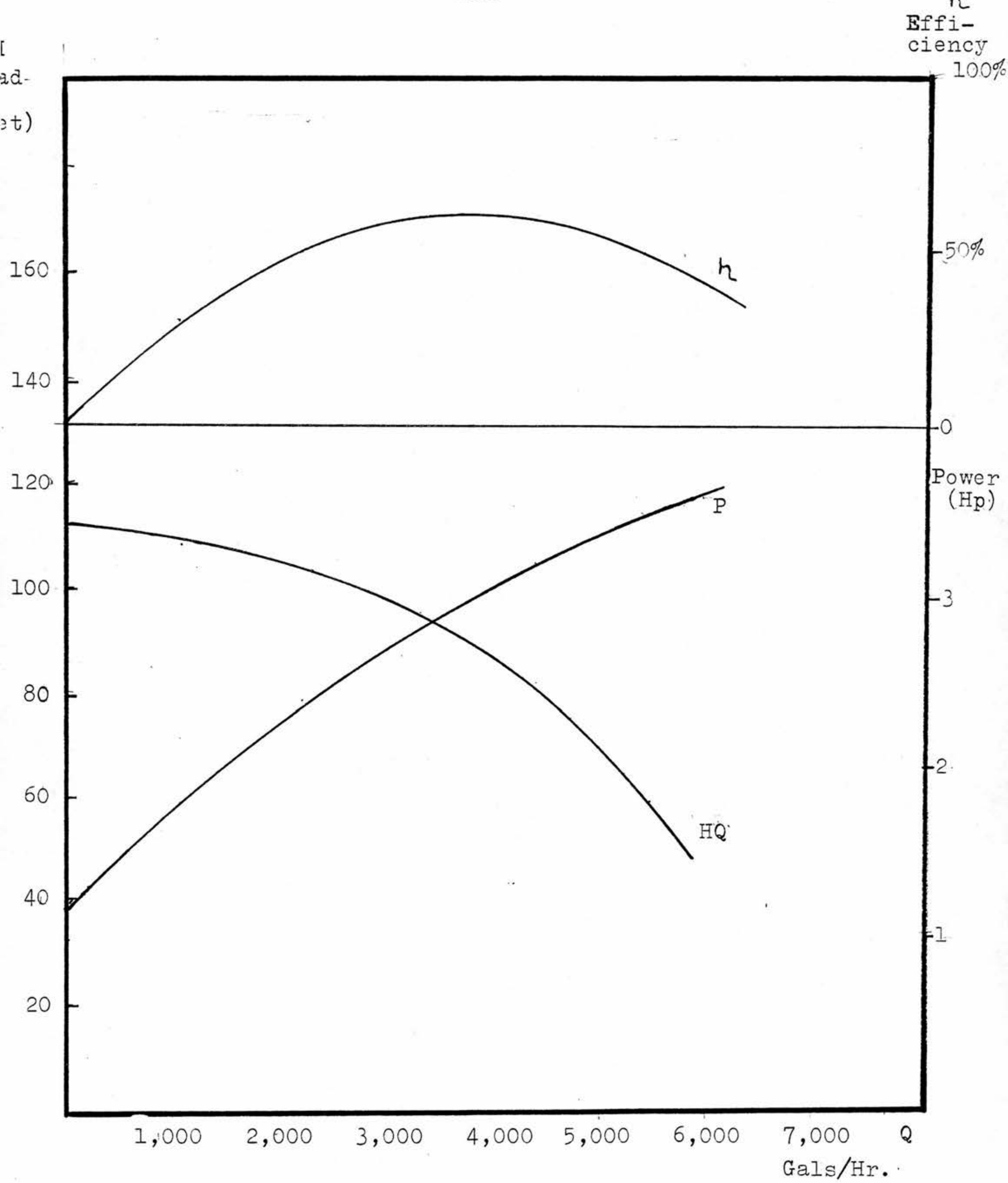

Figure 5.2 Pump Reference Chart.
Source: Alfa-Laval Dairy Book.

generates centrifugal force, creating a centrifugal acceleration α. α is not constant but increases with the distance from the axis of rotation (radius r) and with the speed of rotation, expressed as angular velocity (ω). The acceleration is calculated from the formula

$$\alpha = r\,\omega^2$$

Sedimentation velocity in a centrifuge can be up to 6500 times faster than that experienced if the fat or dirt is allowed to settle out by gravitational force.

The amount of fat that can be separated from milk depends on both the design of the separator and the rate at which the milk flows through it. The centrifugal separator is designed to work at a given flow rate, separating (say fat from milk) with a given efficiency.

5.1.3 Other Engineering Principles

a) Mass transfer principles

Mass transfer operations involve mainly concentration, evaporation, drying and washing of butter and cheese curd. In the processing of pasteurized milk, there are very few instances of mass transfer operations except for those involved in cleaning and packaging.

For cleaning mass transfer principles are involved in the application of cleaning solutions to the fouled surface, the scraping and removal of materials and the agitation necessary for the "scrubbing" of the surface. These activities involve principles relating to velocity and turbulence. However, for assessing the energy consumption by various cleaning systems, the technical specifications of the manufacturer provide enough information for this particular purpose.

b) Power transmission principles

Equipment may be driven by direct shaft connection to a motor, or for lower speeds, to a geared-head type motor. In some places a chain or belt must be used and a variable speed drive may be necessary.

The horsepower transmitted by shafts and belts (maximum is calculated by using the equations[1]

$$hp = \frac{D^3 \times R}{50} \quad \text{for live shafts}$$

and $$hp = \frac{D^3 \times R}{30} \quad \text{for counter shafts}$$

where

D = Diameter of the shaft in inches, and

R = Revolutions per minute.

The maximum hp which a two-ply flat leather belt may transmit is given by this empirical formula

$$hp = \frac{V \times W}{1{,}000}$$

where

V = Velocity in feet per minute

W = Width of belt in inches.

The load carrying capacity of belts depends on belt speed, cross section of belt and diameter of pulley among other things, details of which are provided by the manufacturers.

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1 From Farrall (1963, p. 27).

5.2 The Physical Variables

The second step in the transition from basic engineering relationships between inputs and outputs to the more familiar economic relationships is the identification of the physical production factors and their contribution to output. In the type of exercise that is being done in this thesis the physical form of the input variables assume great importance. This is because any effort to derive production functions from the strict engineering variables (heat, thickness, pressure, etc.) would not only be a frightfully complicated task but would provide alternative combinations of variables which would be unidentifiable in terms of available production technologies and would involve the redesigning of equipment and processes.

Since it is selection rather than redesigning which is the objective of this thesis, the physical relationships provide a convenient halfway house through which output can be related to the engineering inputs. The physical variables chosen, therefore, must be such that their values can be drawn from engineering data using some of the engineering principles, and, at the same time, their values must be easily converted to economic values for economic analysis.

With this in mind, the physical input factors relevant to the pasteurization process, are considered in the following broad categories.

1. Physical Capital
2. Labour
3. Energy
4. Other Utilities.

Within these broad categories the physical factors are further disaggregated as they are related more closely to their engineering basis. These broad categories are examined in turn.

5.2.1 "Physical" Capital

In keeping within the scope of the analysis, which is limited to in-plant production processes, to the exclusion of distribution, marketing and other external activities associated with the product, the physical capital variables to be considered are

a) Equipment systems, and

b) Floor space.

Floor space is used as a guide to the overall building size required for producing the pasteurized product and is dependent to some extent on the technology chosen. Because marketing and distribution activities are excluded, no consideration is given to rolling stock as the choice of vehicle and associated expenses are not in any obvious way dependent on the in-plant technology chosen.

a) Equipment systems

In order to avoid masking over the actual physical distinctions between one type of capital investment in plant and any other, physical variables can be used which allow the identification of particular bits of equipment and equipment systems.

For any defined intermediate output, it may be possible to identify one or more pieces of equipment or equipment systems which can produce the identical output both in quantity and quality from a common defined input. These systems would, very likely, require different combinations of the other co-operating physical factors, wherein lies one of the bases for choice. As an example, consider a fixed quantity of an input commodity and an intermediate output commodity, both closely defined by their physical characteristics, such as the input to a pasteurizer and the output from it. The input may be described as "1,000 gallons of milk containing pathogenic organisms with a temperature of $39^{\circ}F$", and the output described as "1000 gallons of milk 99% free of pathogenic organisms with a temperature of $39^{\circ}F$". There may be endless engineering possibilities for combining solid materials, with heat, pressure, work[1] and other engineering variables to produce this same output. However, a limited number of equipment systems (pasteurizer vats of limited designs, heat exchanger plates in series, etc.) have actually been designed.

From the engineering systems that have been designed, using the various engineering principles and the analytical and synthetic (experimental) design laws, the physical fixed capital component can be identified. It is, however, not only difficult but virtually meaningless to try to compare different alternative designs of fixed capital by trying to measure the differences in material composition by strength of material, density, thickness, emmisivity, conductivity and other such engineering design criteria. This is because the actual comparative purchase prices of the competing equipment systems need not bear any fixed relation to all or any of these design criteria, in a way that would provide any basis

1 A term referring to all types of energy (e.g. kinetic, fossil free, etc.).

for a cost analysis of the alternatives.

To compare alternatives in fixed capital for producing a given output, therefore, the existing physical designs must be the first basis for comparison and this comparison can only proceed with knowledge of the actual prices charged by the manufacturers for the different equipment pieces or systems for performing a given operation or combined operations designed to have the desired effect on the input. Thus all considerations of fixed capital alternatives must ultimately be reduced to cost comparisons.

However, by maintaining the individual designs as discrete and distinct alternatives, each with a price tag attached, the realism in technological choice remains intact with respect to plant capital, and the basis is there for further cost analysis when the other physical factor proportions are being evaluated. Account can then be taken of depreciation and the cost of capital services (interest charges), when the cost of the other factors is being taken into account (see Section 7.1).

Another advantage to be derived from maintaining the physical description of the capital variable, even though it gets represented by a monetary value, is that it then becomes possible to analyse the effects of the different equipment systems on the output characteristics of the product (intermediate) when the system is used to process a defined input (defined in terms of quantity and quality). The difference in output need not be in terms of intrinsic qualities, but may relate to the speed or rate at which the output is released for the next operation, and to the type of output such as, whether it is discrete or continuous.

In the analysis of scale factors with regard to any individual type of equipment or equipment system, it is again advantageous to have knowledge of the engineering design variables, as, in some cases, scale cost trends may depend on one (or more) design variable. In addition, the physical quantities and proportions of the other physical factors associated with the equipment of the design in question, can usually be related to the scale factor of the capital equipment as measured according to that design variable. The key design variable can take the form of the speed at which the machinery operates, the heat it can transfer, the volume (e.g. of a tank), or some such characteristic.

b) Floor space

Equipment manufacturers and suppliers usually furnish information on the dimensions of the floor area which will be occupied by the particular piece or system of equipment. By using various formulae to relate equipment area to total area it is possible to overcome one drawback of this micro approach where there is a tendency to focus on the equipment systems alone, ignoring overhead plant requirements. The floor space variable provides the necessary link.

Certain rules of thumb are used by dairy engineers to decide on the size of the plant that needs to be constructed. According to Farrall (1963), the minimum floor area required for a processing room for a particular equipment system (A) may be determined when the area occupied by the equipment is known by applying the formula

$$A = 5a$$

where

$$a = \text{area occupied by the equipment.}$$

Thus for every piece of equipment or equipment system, a corresponding value for plant floor space can be derived and costed for an analysis of the total costs associated with that alternative.

In addition there are other rules of thumb for computing plant space which can be linked to that arrived in much the same way as above to provide additional information on the space required for other areas of the plant other than the rooms in which the equipment stands.

Using the same source as above, these rules of thumb relate not only to the equipment floor space but also to the volume of milk being handled, and, in one case, (see (a) below), to the packaging technology chosen. These rules of thumb include

i) the size of the milk storage room may be based on approximately 5¼ gallons of milk per square foot if bottling is done in round bottles, or 7½ gallons per square foot if square bottles are used. For paper cartons the estimate is 11¼ gallons.

ii) the refrigeration machinery room (compressors, ice plant, etc.) in fluid milk plants requires from 0.60 to 1.0 square feet of floor space per hundredweight of milk handled per day.

iii) A boiler room will be usually from 0.4 to 0.8 square feet for each 100 pounds of milk per day (excluding fuel storage).

Other more easily applied rules of thumb ignore technology differences, and also ignore specifications for individual areas and relate overall floor space required for the plant to the volume of the milk being handled per day.

Mitten (1949) suggests:

i) For volumes under 20,000 pounds daily, as much as 3 square feet per gallon should be used; and

ii) for a medium size plant, the area should be from 1 - 2 square feet per gallon of milk handled per day.

In relating floor space to the actual area required by the equipment system (at least for the processing area), the implications of technology choice extend to the fixed capital in buildings. Thus the present approach would tend to favour this rule of thumb for determining the processing floor space requirements, which can be used together with the rules of thumb which relate auxiliary areas (storage rooms, etc.) to the volume of milk being handled.

5.2.2 Labour

In deriving an engineering production function from first principles it is possible to calculate the amount of work required in performing a particular task or operation, and then to consider the ways in which this work requirement could be accomplished using various combinations of the many forms of energy, as appropriate. However, as discussed under 5.2.1 (above), going back to these first principles would lead, most certainly, to the consideration of alternatives which do not exist in commercial form and more so, may be even extend beyond current technological capabilities.

Thus, it is far more practical to consider the processes as equipment based and to consider the design of the equipment available and the quantity (and type) of labour that must be associated with it.

There are, however, two nagging problems concerned with the measurement of the physical labour variable. These relate to a) distinguishing between men and man-hours and b) taking account of X-inefficiency.[1]

a) <u>Men vs. man-hours</u>

It is very rare to find any engineering literature or manufacturers' technical specification sheets which make any reference to the amount of labour (however defined) required to be used with the equipment. The determination of the labour requirement is often left largely to actual observation of the equipment in operation in the plant setting, and also partly to intuition.

One of the problems involved in computing labour requirements derives from the situation in which one man may be able to attend to more than one piece of equipment or machinery, while they are both in operation. Thus, if it is considered that the two equipment systems can be operated by one man each in isolation, but without fully utilizing him, then by summing the labour requirements for these two equipment systems, the total number of men shown as required is excessive, and in the actual plant situation one man is redundant.

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1 A concept akin to overmanning (see Leibenstein (1966)).

Many of the studies done on labour requirements in the dairy industry[1] have favoured the man-hour approach by computing the amount of time one man must devote to the attention of any particular piece of equipment. The advantage of this method is quite obvious. What is less obvious is that the co-ordination of men and activities to such an extent, that all the workers are always performing tasks, is highly unlikely and largely impractical. It is only if this were true that the sum of the total man hours required (even accounting for slack in attending to a job) would be equal to the total man hours that will materialize in an actual plant situation.

Men are usually paid by the day or by the week rather than by the number of hours spent performing tasks. Thus when wages are converted to hourly figures for convenience they may include payment over idle time and over lunch time and tea breaks. Also the real-life plant requires some flexibility in the manning position to accommodate absenteeism and other contingencies in the plant.

One way of mitigating the effects of the distortions that could be caused by the man-hours approach is utilized in the staged optimization procedure being used in this thesis, namely to allow what may be described as a "contingency and idle-time" factor for each man-hour represented by some fraction of the man-hour.

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1 See, for example, U.S. Dept. of Agric. Marketing Report H232.

b) X-inefficiency

For tasks which involve a relatively large amount of manual work, it is often very difficult to compute the number of man-hours required for the job and indeed any estimate of this must to a large extent depend on the efficiency level of the work force.

Since there are no firm basis for arriving at any ideal or desired level of speed at which men can or ought to work in a plant, then some method must be found for using the results of empirical studies on labour requirements.

Much of the information on labour hours required for performing manual tasks (e.g. manual reception methods, manual washing of cans) relate to conditions in the United States. The United States Department of Agriculture Study provides vèry detailed information on labour capabilities and man-hour requirements for a number of operations in milk plants in Mississippi[1].

Efficiency levels in the United States of America are known to be particularly high and so these data may be of little value when used in a different socio-cultural setting. Thus it is useful to test the sensitivity of the optimal choices to variations in efficiency levels of labour from that found to exist in the U.S.A. Thus, in addition to varying relative factor prices, labour efficiencies can also be varied. The greater number of man-hours required for performing certain operations may partially offset the lower wage rates in countries with lower efficiency levels where the firm operates

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1 U.S. Department of Agriculture (op. cit.)

inside, rather than on, the production frontier.

Many of the pasteurizing plant operations, however, may be described as machine paced. Thus, the manufacturers can quite easily indicate that, for example, one worker must be in attendance at the machine for the full elapsed time of the process. The man-hours per unit of product can then be computed on this basis. In many cases manufacturers have been able to provide such information for this study. In addition, after visiting dairy plants, and studying their operation, it was possible to identify the proportion of a machine operating time that attention by a worker was required.

5.2.3 Energy

Although labour provides energy for many of the activities in the pasteurizing plant it is useful to distinguish this form of energy from the other forms of energy which can be utilized by going back to the engineering principles behind the design of the equipment. These energy requirements are determined largely in relation to a) motor requirements and b) steam, hot water or refrigeration requirements (heat transfer operations).

a) Motor energy

Motors are used for the purpose of i) the pumping of liquid, ii) the conveying of materials (materials handling) and iii) the driving of power machinery in general.

i) Energy for pumping

In the case of the pumping of liquid, the formula for estimating the pump horsepower required was given in Section 5.1. Some manufactures indicate the appropriate size of the pump to be used with their equipment. Thus in some cases, it is only a matter of converting the motor hp into electricity and this has already been discussed. Where this hp rating of the pump is not disclosed, returning to engineering principles gives the desired value.

ii) Materials handling

When the choice is made to convey materials by conveyor belt, the size of the motor required is related to the width of the belt, and the velocity, among other variables.

Again, with conveyors designed for a certain speed and a certain purpose, the motor hp may be specified by the manufacturer. The desired speed of the conveyor must match the design of the equipment which it serves (e.g. the conveyor carrying bottles from bottle washer to bottle filler must operate at speed to suit the filling rate of the filling equipment).

Failing this, the required motor hp can be derived and converted to electrical energy (kilowatt hours), which is the appropriate intermediate variable to represent the engineering variables (velocity, load, etc.).

Much of the conveying in dairy plants is done using chain conveyors. There are several factors which determine the load and hence the horsepower required for the chain conveying operation. These include: the weight of the chain per foot of conveyor; the average weight per foot of packages conveyed empty or full per foot of conveyor; the number and type of curves, the pitch of the conveyor, the coefficient of friction; the speed of chain in feet per minute; and length of the conveyor in feet.

Farrall (1968) gives the formula for calculating the required horsepower as

$$\text{Hp} = \frac{\text{lbs. chain pull} \times \text{chain speed in ft/min.}}{33{,}000}$$

where

lbs. chain pull = (Average weight/ft of package + weight of chain/ft) × length of conveyor in ft. × coefficient of friction.

For single and multi-wheel curves of 30 to 90, 5 ft. of straight conveyor is considered the equivalent. This increases to 10 ft. for curves of 90 - 180°. A bar curve of 20-45° is weighted 40 percent of the accumulated curve up to the curve. This becomes 50 percent where the bar curve is 46-90°. In a pitched section (incline) 10 percent is added to the chain-pull for each ½ inch per foot increment above the level. The coefficient of friction is .33.

iii) Power driven machinery

Much of the machinery and equipment used in the pasteurization plant require the use of electric motors for driving some moving part of the equipment. Where the energy requirement is not substantial, instead of referring to the motor hp required, the equipment usually has an electrical rating.

This rating is usually expressed in KVA or (Kilo-volts-Amperes) where watts = volts × Amperes and Kilo (1,000) allows the rating to be given in the unit of electricity, the kilowatt, on which electricity charges are based.

b) Energy for heat transfer operations

i) Energy for the production of steam

By considering the design of the heat exchanger being used for a particular heating operation involving steam, the quantity of steam required can be determined using the engineering principles described in Section 5.1.

It is assumed that the steam is produced within the plant in a steam boiler, rather than being "bought in" from an outside source. Knowing the steam requirement, and boiler efficiency the boiler Btu and hence the boiler hp required can be computed. Knowledge of the thermal efficiency of the boiler fuel allows the steam requirement for a particular design of heat transfer equipment to be converted into a requirement for the particular boiler fuel, on which energy costs can be based.

It is generally useful, therefore, to separate the energy required for a heat transfer process involving steam, from the energy required for other heat transfer processes (involving hot or cold water or direct expansion refrigeration) and for driving motors, since the first (steam) leads to a physical variable represented by a primary fuel (coal, gas, oil) whereas the others lead to the Kwh as the "physical" variable.

ii) Energy for hot/cold water and refrigeration

The principles of heat transfer described in Section 5.1 provide the basis for converting the energy required for these operations into the unit of electric energy (Kwh).

Account must also be taken of the design of some equipment to allow regenerative heating and cooling, minimizing the need for additional heating (or cooling).

5.2.4 Other Utilities

Some account can also be taken of the way in which the equipment design affects the consumption of water, compressed air and other miscellanea in the plant. The consumption of compressed air is costed in relation to the size of compressor required for its production and the horsepower of the motor. Thus, unlike water, the air itself is not the variable which is costed.

When the water used in a heat exchanger is being recycled or reused in some other activity then its value may be negligible and not worth including in the analysis. Where a cooling system involves the closed circuit for the circulation of cold water or bring the same applies as above.

5.3 Data Problems

An engineering study of this type requires a substantial amount of information gathering. This required consultation with the available literature on Dairy Engineering and food product engineering in general, interviews with manufacturers of equipment and visits to dairy operating plants.

5.3.1 Dairy Engineering literature

Generally, the available texts on Dairy technology and engineering[1] were reasonably adequate for this purpose, even though somewhat out-of-date in relation to the technological characteristics of some of the currently available equipment. For an understanding of the engineering principles involved in the design and functioning of the equipment the available literature was an invaluable source of information.

With the more recent interest in the field of Engineering Economics, some texts in this area[2] were able to provide very useful information on the way in which cost varied with some particular aspect of the design of individual pieces of equipment or equipment systems.

The problem which remained was to try to obtain current prices of equipment for use as the capital variable. It was necessary to ensure that the prices for the same year for different designs of equipment were obtained to allow comparisons to be made of "physical" capital content of the equipment. In addition, if the computations to find the energy requirements for pumps, motors, heat-exchanger and other types of equipment, were to be kept to a minimum then further details of the required capacities of the energy generating equipment compatible with the equipment systems, would be required from the designers and manufacturers of the equipment.

Some of the available literature included studies done of dairy plants[3] in which a basis was provided for comparing relative price tags on indidivual equipment systems of

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1 See Farrall (1963); Lampert (1970), Harper & Hall (1976); Hall (1968); FAO/WHO (1963).

2 See especially Happel & Jordan (1975) and Peters & Timmerhaus (1968).

3 See especially U.S. Dept. of Agric. (op. cit.); Hall, C.W. (1952).

of different designs. However much of the other literature on Dairy Plant studies was of too general a nature to provide very useful information.[1]

5.3.2 Dairy Equipment Manufacturers

In addition to providing information on the "physical" variables, data were also required on the economic life of equipment and its scrap value to allow the annual costs of equipment systems to be computed. Details of the time necessary for repairs and maintenance of the equipment and the annual cost of spare parts were all necessary for the economic analysis to proceed.

The questionnaire sought to obtain data on the price of an equipment unit and all the necessary accessories (pumps, compressors, necessary conveyors, etc.), and to have an estimate of the installation cost. Questions on Floor Space, expected life, spare parts required and scrap value were all designed to extract the information necessary for estimating the annual capital costs.

Manufacturers were also asked to give a figure for the number of workers they regarded as being required for the entire, or a proportion of the length of time the equipment was in use.

In an effort to avoid detailed energy conversion calculations, explicit details were requested on the horsepower (or kVA rating) of the equipment and its basic accessories. Questions on steam and water consumption were also asked.

The answers to all questions were sought in relation to

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1 See, for example, Conner, Boehm & Pardue (1976); Hurt V. (1953).

specific capacities of equipment. The full questionnaire is included as Appendix 5.1.

The response from Equipment manufacturers was mixed, with varying degrees of co-operation ranging from that given by the more enthusiastic management personnel who freely gave all the assistance they could, to those who declined to give away any of their "secrets".

Fortunately, however, the larger companies involved in the manufacture of Dairy equipment were the more forthcoming. Among the smaller companies, many produced similar types of equipment which meant that the disinclination shown by any single firm did not result in a severe gap in the data.

One notable feature was the generally poor response to written requests for information. In view of this personal interviews with manufacturers had to be carried out.

In all, some eighteen firms manufacturing or supplying dairy equipment were asked to take part, of which fourteen gave some type of positive response, two declined on the grounds that they no longer considered themselves suppliers to the dairy industry and two refused completely to become involved.

With regard to technical data most of the responding firms were quite willing to supply this type of information, although for firms which were just suppliers rather than manufacturers the information seemed limited to little more than what was available in the brochures supplied to prospective clients.

By contrast, there was much hesitation to provide information on cost data, with some firms being concerned that their competitors should learn of their prices. The larger international dairy equipment manufacturers were less cagey about revealing prices, perhaps because they fear the competition less. In every case, however, the firms asked for strict confidentiality, particularly with regard to prices and so in the cost analysis that follows, manufacturers' names will not be divulged in relation to any of the data on the price tags attached to the physical capital equipment. The data are revealed only in a general way without specific reference to brand names or to specific manufactures.

Fortunately, dairy technology is an area in which very much is known about the designs and characteristics of the equipment, and these basic equipment designs are available world wide. In addition, although all the interviewing was done in Britain, the major manufacturers are all subsidiaries of international companies manufacturing and supplying dairy equipment on a global scale. Thus the data being used are not restrictive and limited in their applicability to a particular corner of the globe.

One problem however was in getting access to data on types of equipment now considered obsolete by the large equipment manufacturers (e.g. vat pasteurizers, milk cans, reception systems). However, the smaller manufacturers supplying this older technology, which is still used in many parts of the world, were able to provide the necessary information.

5.3.3 Dairy Processors

Certain necessary details of equipment are better provided by those who operate the equipment. This is particularly so with data concerning labour use, breakdown rates and repairs and maintenance. In addition, the alternative combinations of equipment systems and the way in which they interact are better understood when they are directly observed.

Again the response to requests for visits and for answers to a questionnaire varied. One firm completely refused to have anyone visit the plant, declining to complete the questionnaire, including even the parts they considered less sensitive. This was surprising in view of the relative ease of accessibility to data on dairy equipment and on the techniques used in the plants.

The questions asked were related to the technical side of the operation rather than the more sensitive area of costs. The aim was to get some back-up data required to establish the "physical" values of production variables.

The Dairy processing production managers were asked about the daily throughput volume and about the capacity of the respective equipment units in the plant. The questionnaire also sought to estimate the extent to which capacity might be underutilized at any point(s) in the process.

The opportunity was taken to ask details of labour and energy use in the actual plant situation. Questions relating to the consumption of thermal and electrical energy were asked.

The questionnaire used in interviews with dairy processors is included as Appendix 5.2.

CHAPTER 6

THE QUANTIFICATION OF THE PHYSICAL FACTORS OF PRODUCTION

Evaluation of the alternatives must proceed by first quantifying the physical factors associated with the respective alternatives for carrying out the processing operations at the various stages of the production process.

The engineering principles explained in Chapter 5 are applied, where necessary, to convert certain engineering design variables into physical factors to which, in turn, economic cost values can then be attached. The principles of hydraulics and pumping, for example, are applied, where this is necessary, in determining the required pump horsepower. Knowledge of the heat transfer principles allows the assessment of heat requirements for the particular job and the conversion of heat units to be added or to be removed, into boiler fuel or refrigeration electrical energy requirements. The resulting variables are those to which prices are usually directly attached.

In this chapter, the alternative combinations of physical factors along the production line are studied in some detail, and are quantified to provide a basis for the economic analysis which follows in Chapter 7. The broad groups of operations, categorized here as: Reception; Central Processing; Finishing and Auxiliary operations, are simply more convenient ways of grouping the operations described for pasteurized milk processing in Chapter 3 (Section 3.2.2). Operations are linked together where the equipment systems available are usually designed to cover that cluster of operations. To try to separate and consider alternatives for each operation would involve some measure of "redesigning", which is not the purpose of this study.

In quantifying the physical variables, the plant equipment factor input is first described in purely physical terms. However, because of the heterogeneity of the various components in the alternative technologies considered at any stage in the process, the physical plant factor is reduced to a common monetary denomination. This is achieved by using the cost price plus installation charge fixed by the manufacturer. The use of these cost figures to represent "physical" capital, does not in any way invalidate the applicability of the "physical" factor quantities to a variety of economic environments, as is proposed in this thesis, since, as mentioned previously, the major dairy suppliers are largely international firms, equipping dairy plants throughout the world.

In quantifying the physical factor requirements certain assumptions are made. These are:

(i) the containers arriving at the dairy bringing the raw milk, are full.

(ii) the arrival of the raw product is continuous (tankers or trucks loaded with cans arrive on schedule).

(iii) All the milk delivered to the plant is processed the same day.

(iv) there is no wastage of labour units(i.e. where a worker's attention is required only 25% of the time then that worker can be attending to other activities during the remainder of the time for that process).

In most cases, however, the labour units are allocated to a process for the full elapsed time of that process.

The cost figure given to represent the "physical" capital, includes costs for the major equipment system plus all the necessary accessories (e.g. pumps, compressors, necessary piping, conveyors etc.).

Data on the quantities of the physical factors required by the respective alternatives for the various operations (or groups of operations) are presented in Tables 6.1 - 6.4.

6.1 Reception Alternatives

The operations considered under the heading "Reception" are those listed under "Preliminary operations" in Chapter 3 (Section 3.2.2), describing the sequence of operations in a pasteurizing milk plant. Because of the way in which equipment systems are designed, it is usually not feasible to consider alternatives for each individual operation. Equipment systems tend to cover some multiple of unit operations for which the component parts of the system must be compatible. Some reference has already been made to this feature in Chapter 3. The approach here, therefore, is to take a modular view of technology, considering as a module, a set of unit operations for which equipment systems are designed.

In this section, therefore, two broad groups of operations are considered. These are (1) Primary reception operations (operations i through iv of the preliminary operations in (3.2.2) and (2) Secondary reception operations (temporary storage and cooling).

6.1.1 Primary Reception Operations

The first two preliminary operations listed in Section 3.2.2 (conveying into the plant of the raw milk, and the weighing and/or measuring of the milk) may be viewed as a single module. They are both simultaneously considered in the design of the alternative reception systems. The testing of the milk for butterfat (preliminary operation (iii)) is fairly standard and need not receive explicit consideration. Preliminary operation (iv), the cleaning and sanitizing of the reception containers, is considered as a separate operation although related to the basic system selected for the first module (Preliminary operations i and iii).

The two broad competing technological alternatives for these primary operations are a) the tanker reception system and b) the can reception system. Within these broad groups competing alternative system technologies may be identified and their use of the physical factors of production assessed. This assessment is done with respect to the factors used at the plant site only.

a) Tanker Reception Systems

For milk supplied to the pasteurizing plant by bulk tanker, the quantification of physical factor requirements for the first group of operations (conveying of milk in to plant, weighing/measuring of milk) is done for three alternatives. These are classified, by the method of weighing or measuring, as follows: i) the in-line metering system; ii) the load cell system; and iii) the weighbridge system. The cleaning of containers is taken into account for each alternative.

As with can reception systems, the cost of the container (cans, tankers) is not included in the analysis at this stage. The scope of the study can, however, be extended to cover this aspect of physical capital which, at the moment, is being considered as external to the plant. No floor-space variable is being allowed for tankers, since, after having visited dairy plants, it became clear that a sheltered area for discharge of the milk is optional.

i) <u>The in-line metering system</u>

The milk is conveyed from the tanker into the plant by being pumped through a line. A meter is attached to the line to record the volume of the milk flowing through the line. In this meter, a small impeller is turned by the flow of milk through the pipe. The impeller is magnetically connected to an electrical circuit which, in turn, carries an impulse to a recording meter. Figure 6.1 shows a tanker off-loading milk using the in-line meter system.

The basic equipment requirements, therefore, are the line, the meter and the pump. In addition to the above, a de-aerator[1] is considered essential for greater accuracy in metering, and this will be included as a standard requirement for the purpose of this analysis.

Control of the milk reception may be manual or automatic. In the automatic system, the pump is started automatically, by the control equipment which senses when the de-aerator

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1 This is positioned ahead of the meter to remove the air from the milk before the milk reaches the meter.

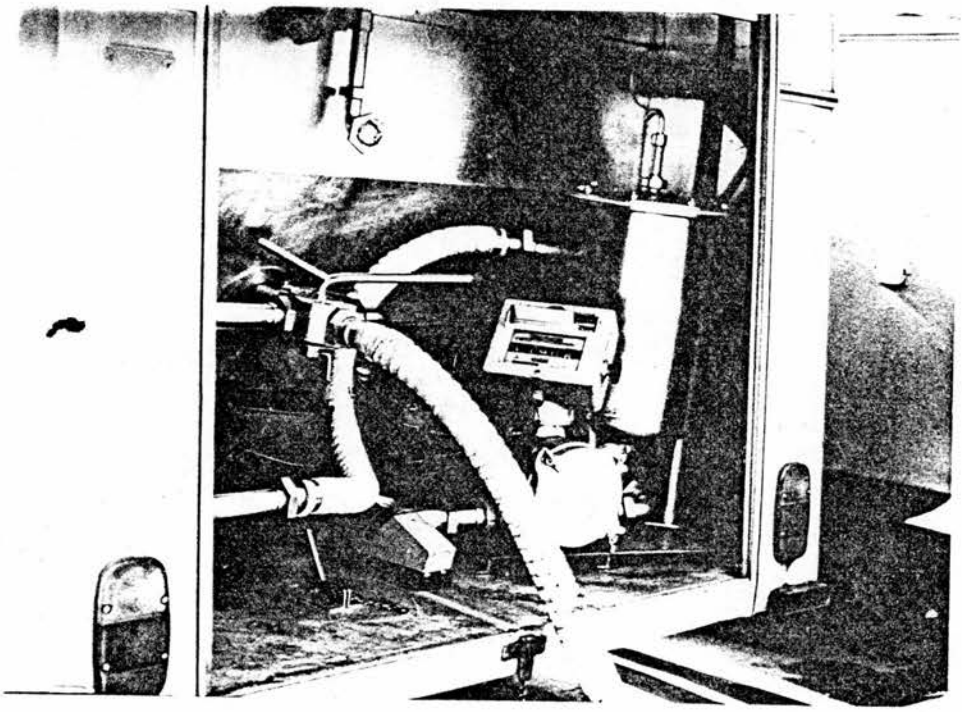

Figure 6.1 In-line metering reception
Tanker offloading at dairy.
(Courtesy of Edinburgh Dairies)

has reached the set level for preventing air from being sucked into the line. It is also stopped automatically when the level drops below a certain point. This automatic system requires the use of a microprocessor and a special set of valves in the intake line.

Alternatively, a manual control system may be used. Here the action of the pump is instigated by push-button and manual valves are used in the intake line.

The physical variables are assessed for both the automatic control system and the manual system, and will be based on the factors required for one input line, using the assumption that where scale up is by replication, the factors increase in direct proportion to the number of the replications.

The physical quantities of the factors required for line systems are related to the rate of product flow through the line. Thus quantification of the physical variables depends on the application of fluid flow principles set out in Chapter 5.

Physical fixed capital

The basic equipment requirements for a single line are

(1) The milk meter (with de-aerator) and including 20 ft. hose pipe.

(2) The pump.

(3) The piping (line).

(4) Manual valves for a manually controlled system; automatic valves for microprocessor system.

(5) No cleaning equipment is considered, as the cost of the hose and brush for tank cleaning is negligible.

Except for the milk meter, the quantities of the other components of the system vary with the rate of milk intake from the tanker. In the case of the pump, the variation is in pump-horsepower. For the piping, the variation is in pipe diameter as cost per foot is usually based on this design variable. The use of the automatic controls may be taken to raise the cost of the valve components, increasing line costs by a factor of 10, and this can be applied throughout the plant.[1]

Using fluid flow principles the equipment requirements may be determined. These components may be quantified as follows, in relation to a single line and single intake flow rate:

I Milk meter (with de-aerator) - one (1).

II Pump Capacity (Hp). Using a given intake flow rate (gals/hr) the required pump horsepower may be read off from Figure 5.2.

III Intake pipe line and fittings - The "ideal" diameter may be determined from Figure 5.1, with knowledge of the ideal velocity for milk (see Chapter 5).

In computing the basic purchase price plus installation cost for these components of the in-line metering system to represent the "physical" fixed capital variable, the following points may be noted.

A) the cost of the meter and de-aerator is invariant with the intake flow rate.

B) the pump cost is related to the motor Hp of the pump. The average size exponent (n) for motor Hp between 1 and

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1 Information supplied by equipment manufacturers.

10 (the values relevant in this case) the exponent is given as 0.37. Thus,

$$\frac{(\mathrm{Cost})_B}{(\mathrm{Cost})_A} = \left(\frac{(\mathrm{Hp})_B}{(\mathrm{Hp})_A}\right)^{0.37}.$$

C) The piping cost is generally considered to relate to pipe diameter such that a plot of the logarithm of the pipe diameter versus the logarithm of the purchase cost per foot of pipe is essentially a straight line, and so the following equation is used:[1]

$$C = X\, D_i^{\,n}$$

where C = purchase cost of pipe per foot of pipe length

X = purchase cost of pipe per foot of pipe length if the pipe diameter is 1"

n = 1.5, for steel pipe where the diameter is over 1" such as in the intake line

D_i = Diameter size i.

The installed cost of pipe and fittings are usually correlated as functions of the pipe diameter. Some data on piping and valve costs have been obtained from the dairy equipment manufacturers.

The basic capital costs for the in-line metering system have been computed for discrete intake flow rates with intervals of 1,000 gallons per hour.

Labour requirements - Man-hours

The first labour activity involved is the positioning of the tanker truck for discharge of the contents. Although the truck driver does the actual manoeuvring of the vehicle, a plant worker guides the driver. The worker also checks the

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1 Peters and Timmerhaus (1968, p. 304).

odour and appearance of the milk and a sample may be taken to check for butterfat. Using U.S.A. labour efficiency standards (as explained in 5.2.2(b)), this activity takes 2.40 minutes and is done by one man (0.04 man hrs.).

This activity has to be performed on each tanker truck. It is assumed that the tankers would be timed to arrive so that the milk may be discharged virtually continuously. Thus, while one tanker is being discharged, the next one is being positioned and checked. In this way, the number of tankers is not relevant and the checking activity is counted only once.

The second activity involves connecting up the tanker to the discharge line so that the milk may be conveyed in to the plant and metered. The connecting and disconnecting activity along with the insertion of the card for recording the quantity indicated by the meter requires a similar time to the above (0.04 man-hrs per truck). In this case the number of tankers off-loading (total daily volume/capacity of tanker), and the rate at which the milk is received must be taken into account, to give the total elapsed time for this activity.

For the purposes of this analysis, a fixed size of tanker is assumed. Tanker sizes range from 1,000 to 4,000 gallons. In order to allow tanker delivered milk to be considered for the smallest daily capacity being studied here, a standard tanker size of 1,000 gallons is being used. It is assumed that all tankers arriving at the dairy are full.

The truck is then washed out (cleaning operation) and removed from the discharge area. The elapsed time for cleaning out each tank is given as 0.18 hours and with one man performing the task this is equivalent to 0.18 man hours. This cleaning can, however, be done by the plant worker while the next truck is discharging its contents. Therefore these man-hours need only be added once - for the last truck that delays the worker. When the discharge rate is above 4,000 gallons per hour, a second worker is required to assist with the tanker cleaning.

Thus the total labour requirement for the in-line flow meter method for primary reception operations is:

(Initial manoeuvring time) + (Final cleaning and send-off time) + [(connecting and disconnecting time per truck) + (elapsed time for discharging truck)] × (number of trucks).

Thus, total labour requirement

$$= 0.04 + 0.18 + \left[\left(0.04 + \frac{\text{tank capacity}}{\text{discharge rate}}\right) \times \left(\frac{\text{intake volume}}{\text{tank capacity} \atop = 1{,}000 \text{ gal.}}\right) \right]$$

These are the basic physical data on labour man-hours that will be used for an economic evaluation of this alternative. The same labour is required for the push button system as for the microprocessor automatic system, the difference is largely in the increased accuracy which the automatic system affords.

Energy Requirements (Kwh)

The energy requirement is based on the pump motor horsepower which, in turn, is related to the intake rate. The horsepower of the pump motor may be converted to electrical energy requirements using the conversion equation given in Chapter 5 (Section 5.1.2).

A comparison of the physical factor requirements for the different tanker reception systems is given in Table 6.1.

TABLE 6.1

PHYSICAL FACTOR REQUIREMENTS OF ALTERNATIVE TANKER RECEPTION SYSTEMS

SYSTEM	INITIAL OUTLAY (£'000)				ELECTRICITY (KW RATING)				LABOUR (MEN FOR T.E.T.)				STEAM ('000 LBS PER HR)			
CAPACITY	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
1,000	8.9	27.4	17.4	44.4	2.2	2.7	2.3	2.4	1	1	1	2	0.13	0.13	0.13	0.13
2,000	9.4	27.9	17.9	44.9	2.6	3.1	2.7	2.7	1	1	1	2	0.25	0.25	0.25	0.25
3,000	9.4	27.9	18.2	44.9	3.1	3.6	3.2	3.3	1	1	1	2	0.38	0.38	0.38	0.38
4,000	9.7	28.2	18.7	45.2	3.8	4.3	3.9	4.1	1	1	1	2	0.50	0.50	0.50	0.50
5,000	10.0	28.5	18.9	45.5	4.1	4.6	4.1	4.4	2	2	2	3	0.63	0.63	0.65	0.63
6,000	10.0	28.5	19.0	45.5	4.3	4.8	4.4	4.7	2	2	2	3	0.75	0.75	0.75	0.75
7,000	10.0	28.5	19.3	45.5	4.6	5.1	4.7	5.0	2	2	2	3	0.88	0.88	0.99	0.88
8,000	10.0	28.6	19.7	45.6	4.8	5.3	4.8	5.2	2	2	2	3	1.00	1.00	1.00	1.00
9,000	10.4	28.9	19.9	45.9	4.9	4.4	5.0	5.4	2	2	2	3	1.13	1.13	1.13	1.13
10,000	10.4	28.9	19.9	45.9	5.3	5.8	5.6	5.6	2	2	2	3	1.25	1.25	1.25	1.25

NOTES:

1. THE FOUR TANKER SYSTEMS T1,T2,T3 AND T4 ARE AS DESCRIBED IN SECTION 7.2
NO FLOOR SPACE IS ALLOCATED TO THIS ACTIVITY.
WATER USE IS ESTIMATED AT 45 GALLONS PER TANKER.

2. THE SYSTEM CAPACITY REFERS TO THE THROUGHPUT RATE(TECHNICAL CAPACITY) FO THE SYSTEM.

3. INCLUDES INSTALLATION COST AND COST OF ALL ACESSORIES.

4. T.E.T. = TOTAL ELAPSE TIME OF THE OPERATION. THERE ARE ALSO FIXED LABOUR HOURS
REQUIRED FOR INITIAL AND TERMINAL ESTIMATES, THESE ARE FOR
T1,0.26 ; T2,0.22 ; T3,0.22 ; T4,0.26

ii) The Load Cell System

In this system of reception, the milk is pumped from the tanker into a special tank with load cells built into its feet. The cells supply an electric signal that is proportional to the weight of the milk in the tank. As the milk fills the tank, the strength of the signal increases. Thus, when all the milk has been delivered, the contents of the tank can be recorded. The milk is then pumped through the intake line.

In this system, the load cell tank replaces the volume meter. Two weigh tanks are used so that as one tank is being filled up from the discharging tanker, the other load cell tank is being emptied into the plant. A continuous input then results.

The labour hours are decreased only slightly as there is now no need to allow extra time for connecting and disconnecting each truck. This can be done while the second load cell tank is being drained (reduction of 0.04 hrs/truck). The cleaning is done in the same manner as described in (i) above and takes place while another tanker is discharging its contents. No special attention is required for the emptying of the load cell tank.

iii) The Weighbridge System

In this system, the tanker, when it arrives at the plant is driven in to a weighbridge. The weight of the full tank is recorded by the plant worker. After being drained, the empty tank is weighed again and the empty weight subtracted from the full weight.

The physical plant consists of the weighbridge and recording devices; the pump and intake line for conveying the milk into the plant. Alternatively, the milk may be allowed to flow under force of gravity into the plant. In this case, the total elapsed time is longer for the discharging operation. The Standard pump drain method is the one that is considered in the quantification of the physical factors (Table 6.1.).

An additional set of man-hours is required for the activities at the weighbridge. One man is required for the total elapsed time of the weighing operation, while another is required for the draining and cleaning operations, as with the in-line system. A further 0.04 hours is added to the fixed time for tanker reception by the in-line-meter system to account for the initial truck time at the weighbridge.

Where the gravity drain system is used, the cost of the pump is avoided, as is the cost of the energy associated with pumping. The labour hours are increased because of the extended elapsed time of the process.

b) Can Reception Systems

Milk arriving at the plant in cans is treated in the following way: The cans are unloaded off the truck and conveyed into the plant to the point of dumping; the lids are removed and the milk checked for odours and visible contaminants, and samples may be taken (to test for butterfat, etc.) while the cans are being conveyed to the point of dumping; the milk is then tipped into a weigh tank so that the weight may be recorded. It is then emptied out with a dump tank below from which it is pumped to the cooler. Finally, the cans and lids are conveyed to the washing points.

Three types of can reception technologies are examined in some detail. These may be described as: i) the semi-manual system, ii) the manually assisted system, and iii) the fully automatic system.

i) Manual can reception

In the semi-manual system the cans are off-loaded on to a gravity-roller type of conveyor. While they are en route to the weigh tank the lids are lifted manually, and the milk checked and sampled (where necessary). The lids are conveyed to the washing area. The cans are then lifted manually and the contents are tipped over a bar into a weigh tank. The weight is read from a dial scale and recorded by a plant worker. The drained can is conveyed to the washing area. The milk drain valve is then released for the milk to flow into the dump tank beneath the weight tank (or bowl). Manual washing in large vats may also be considered.(fully manual).

Physical plant

The manual system consists of: A gravity roller conveyor; tipping bar; weigh tank and scale; dump tank; pump; draining rack, washer and outgoing conveyor.

With the manual system, cans can be tipped at the rate of 2-3 per minute. Compatible washing facilities would involve the use of a can washer of 2-3 cans per minute capacity of the rotary (or "come back") type (see Chapter 3 (3.3.2)). This may be used as an alternative to fully manual washing. In this washer the cans are placed manually in the washer and the washer is turned by hand so that the cans pass over jets of rinsing water, detergent steam and air.

The worker then removes each can as it comes back to him.

While on the way from the tipping point to the worker, the cans are held over a draining rack so that any milk remaining in the tank, may be drained out and find its way into the weigh tank.

With this manual system, the rate at which the milk is received depends on the rate at which cans can be checked and tipped. Manufacturers consider three cans per minute as the typical figure for a purely manual system.

As with tankers, a standard size of can is being used. The 10 gallon size is reported to be the most popular. An FAO study[1] suggests that can capacities smaller than this would be unnecessarily restrictive, slowing the discharge operations, and would be justified only if the individual farms supplied less than 10 gallons per day to the dairy.

The equipment system is estimated by manufacturers to have an economic life of approximately 14 years with a scrap value of approximately 5 percent of the initial cost in real terms. Spare parts average 2 percent of the initial cost annually.

Buildings

No floor space is allocated to the off-loading operation which is done outside the building. However, unlike tankers, the reception operation is indoors and floor space must be allocated. The building requirements are based on the total floor area required by the equipment. No room is allocated for storage of cans as these are returned to the delivery truck after washing.

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1 FAO Agric. Studies No.23 (1953).

Labour hours

Three workers are usually required to perform the operations involved in manual reception, involving a hand-turned washer. These may loosely be described as the checker, tipper and washer. As the cans are pushed in from the discharging truck to the tipping point, a checker examines the milk for quality, and a sample may be taken from one can of each new supplier's batch. The checker also records the weight of the milk shown on the dial scale, against the supplier's name, and releases the milk drain valve to allow the milk to flow into the dump tank.

Another plant worker, the tipper, removes the lids from the cans as they are enroute to the tipping point and divert them to the washer. After tipping the cans, they are then put on the drain rack and, when drained, are passed over to the washer.

A third worker is required to place the cans and lids in the washer, and to manually rotate the washer, allowing the cans to pass over the jets of water, detergent, steam and air. This worker then pushes the cans on to the roller conveyor for them to be returned to the truck.

The total man hours required would be equal to twice the total elapsed time for the checking/tipping/weighing operation, plus the elapsed time for the washing/conveying out operation. Handling 10 gallon cans at the rate of 3 per minute gives an elapsed time of 0.55 hours for each 1,000 gallons of milk received. With the can washing being done simultaneously with the other operation the same elapsed time may be considered for both activities. This would give a total man-hour figure of 1.65 per 1,000 gallons.

Where manual washing is involved more workers are required to allow the cans to be returned to the trucks. An American study[1] puts the capacity of one worker at approximately 0.5 cans/minute, using a wash vat and sterilizer. Thus a minimum of two men with similar equipment would be required for each can per minute in the reception intake line.

Energy

No energy is required for the gravity roller conveyor or for the tipping and weighing operation. Electrical energy is required for the pump which transfers the milk from the dump tank to the cooler. In addition, energy is required for forcing the jets of water and cleaning agents used in the can washer. The steam used in the washer must also be converted to boiler fuel requirements for a full energy assessment.

Information from manufacturers on pump horsepower necessary for the process, is used to quantify the electrical energy units (kwh) required. Reference to a steam table allows the required quantity of dry saturated steam indicated by the manufacturers, to be converted to boiler heat units (Btu's) to give boiler fuel requirements, with a knowledge of the heat value of the fuel being considered (see Chapter 5).

ii) Manually Assisted Can Reception

In the manually assisted system, the cans are received on a power conveyor with a "cradle" in which the can sits so that it can be pushed over rather than lifted. The weighing is done with the aid of a recording scale, which stamps the weight of

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1 U.S. Dept. of Agric. (1958).

the milk on the producer's receipt when a button is pressed.

The intake rate is speeded up, allowing a faster "straight-through" or tunnel type can washer to be used (see Chapter 3 (3.2.1(c)). The cans are conveyed out on a power conveyor.

With this system, equipment requirements (in money units) are increased. Labour requirements per 1,000 gallons are reduced because of the reduced elapsed time of the process and the redundancy of the third worker in the reception line, (the worker turning the can washer).

The net energy requirements are increased. Additional energy is required for the power conveyor and for moving the cans in the washer. The pump motor horsepower is increased but the pumping time per 1,000 gallons is decreased, leading to a reduction in pumping energy (see Table 6.2).

iii) <u>Fully Automatic Can Reception</u>

With a fully automatic technology, the cans are conveyed on a power conveyor from the delivery truck. On the way to the weigh tank, the lids are removed automatically and diverted to the washer. The cans are tipped automatically into the weighbowl which indicates the quantity. In an advanced automated system, the weighing machine operator registers the producer identification on a keyboard before consecutively weighing in all the cans from that producer. The weights are then automatically totalled and recorded against the identification.

The system is relatively high speed with cans being received at a rate up to 15 cans per minute. The cans when tipped and drained are diverted to a fully automatic straight-through can washer.

TABLE 6.2 (TO BE CONT'D)

PHYSICAL FACTOR REQUIREMENTS OF ALTERNATIVE CAN RECEPTION SYSTEM

SYSTEM	INITIAL OUTLAY (£'000)				ELECTRICITY (KW RATING)				LABOUR (MEN FOR T.E.T.)			
CAPACITY	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
1,000	9.9	13.5	39.6	54.6	-	0.9	19.8	19.8	6	4	2.5	2.5
2,000	19.7	27.0	39.6	54.6	-	1.8	19.8	19.8	12	8	2.5	2.5
3,000	21.5	27.0	40.9	55.9	-	1.8	20.8	20.8	15	8	2.5	2.5
4,000	31.3	40.5	44.2	66.2	-	2.7	20.8	25.1	21	12	2.5	2.0
5,000	41.3	54.0	73.5	80.5	-	3.6	34.1	34.0	27	16	3.0	2.0
6,000	42.9	54.0	74.8	81.8	-	3.6	35.1	35.1	30	16	3.0	2.0
7,000	52.7	67.5	81.4	88.4	-	4.5	35.1	35.1	36	20	3.0	2.5
8,000	62.9	81.0	88.4	95.4	-	5.4	40.4	40.4	42	24	3.5	2.5
9,000	64.7	81.0	89.7	96.7	-	5.4	41.4	41.4	45	24	3.5	2.5
10,000	74.1	94.5	120.3	99.3	-	6.3	55.9	47.7	51	28	5.5	2.5

TABLE 6.2 (CONT'D)

PHYSICAL FACTOR REQUIREMENTS OF ALTERNATIVE CAN RECEPTION SYSTEM

SYSTEM	STEAM ('000 LBS./HR.)				WATER ('000 GALS./HR.)				FLOOR SPACE ('000 SQ.FT.)			
CAPACITY	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
1,000	0.13	0.35	0.40	0.40	0.07	0.20	0.27	0.27	3.2	3.2	3.3	3.3
2,000	0.25	0.70	0.40	0.40	0.15	0.40	0.27	0.27	6.4	6.4	3.3	3.3
3,000	0.38	0.70	0.50	0.50	0.23	0.40	0.31	0.31	6.6	6.6	3.3	3.3
4,000	0.50	1.05	0.55	0.55	0.30	0.60	0.31	0.31	9.8	9.8	3.4	3.5
5,000	0.63	1.40	0.90	0.90	0.38	0.80	0.58	0.58	13.0	13.0	3.5	3.6
6,000	0.75	1.40	1.00	1.00	0.45	0.80	0.61	0.61	13.2	13.2	3.6	3.6
7,000	0.88	1.75	1.15	1.15	0.53	1.00	0.61	0.61	16.4	16.4	3.7	3.7
8,000	1.00	2.10	1.40	1.40	0.60	1.20	0.88	0.88	19.6	19.6	3.9	3.9
9,000	1.13	2.10	1.50	1.50	0.68	1.20	0.92	0.92	19.8	19.8	4.1	4.0
10,000	1.13	2.45	1.65	1.65	0.75	1.40	0.92	0.92	22.0	22.0	4.0	4.0

NOTES:

1. THE FOUR CAN RECEPTION SYSTEMS C1,C2,C3 AND C4 ARE THOSE IDENTIFIED IN SECTION 7.2
2. SEE NOTE 2, TABLE 6.1
3. SEE NOTE 3, TABLE 6.1
4. SEE NOTE 4, TABLE 6.1 THE FIXED LABOUR HOURS REQUIRED ARE C1, 0.08 ; C2, 0.08 ; C3, 0.04 ; C4 ., 0.04

The initial cost of the system equipment is higher and the estimated economic life is shorter (10 years est.) than for the manual system. The average annual cost of spare parts is also a higher percentage of the initial cost of the system. A figure of 15 percent is used by manufacturers. On the other hand, the labour requirement is much reduced. A single worker is required to operate the whole equipment system and the total elapsed time for processing a given quantity is shorter (see Table 6.2).

6.1.2 Secondary Reception Operations

Before the milk moves to the pasteurizer and the associated equipment systems, there is a temporary storage operation which provides a buffer to even out the differences between reception rates and times, and pasteurization rates and times. It is also designed to accommodate emergency stoppages and breakdowns in the plant.

The milk is stored in the insulated tanks at $40^{\circ}F$ ($4^{\circ}C$)[1] and therefore, where the milk received is above this temperature, cooling is required before the milk is passed into storage. The nature of the cooling and storing operations is discussed below.

a) Cooling

Milk received in cans usually enters the factory at a much higher temperature than milk delivered in bulk. The bulk tankers are insulated and the milk for bulk transport is stored on the dairy farms in refrigerated tanks, where it is held at a temperature of, at most, $140^{\circ}F$ ($4^{\circ}C$). On the

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1 Alfa Laval Dairy Book (p. 46).

way to the factory the milk in the tankers may rise a few degrees, depending on the temperature of the country and the distance between farm and pasteurizing plant. Because of this, most plants, even when receiving milk from insulated bulk tankers, usually incorporate a cooler in the processing stream between intake and buffer storage.

Where milk is received in cans, these cans are not refrigerated at the dairy farm, and cooling before storage is therefore mandatory. The milk in the cans is usually at a temperature between 50-60^{o}F (10^{o} - 15.5^{o}C).

i) Plant equipment

The type of heat exchanger generally recommended by dairy engineers for this purpose is the plate heat exchanger illustrated schematically in Figure 6.2. The plate heat exchanger is preferred for its high efficiency in heat transfer), its compactness, low cost, versatility and the ease with which it can be cleaned.

The cooler is made up of a frame or press, with a number of plates arranged to form flow passages for the product and for the cooling (or heating) medium. Terminals form the head or end of the plate stack and provide for piping connections. The plates are arranged to form flow streams and passes, each stream alternating with a passage carrying the cooling medium. Pressures and velocities can be controlled through the arrangement of streams and passes. The milk enters at one end and the cooling medium (cold water or brine) enters at the opposite end.

The capacity of the cooler is given in terms of the rate of the flow of the milk through the cooler, and the cost of the cooler is related to the capacity.

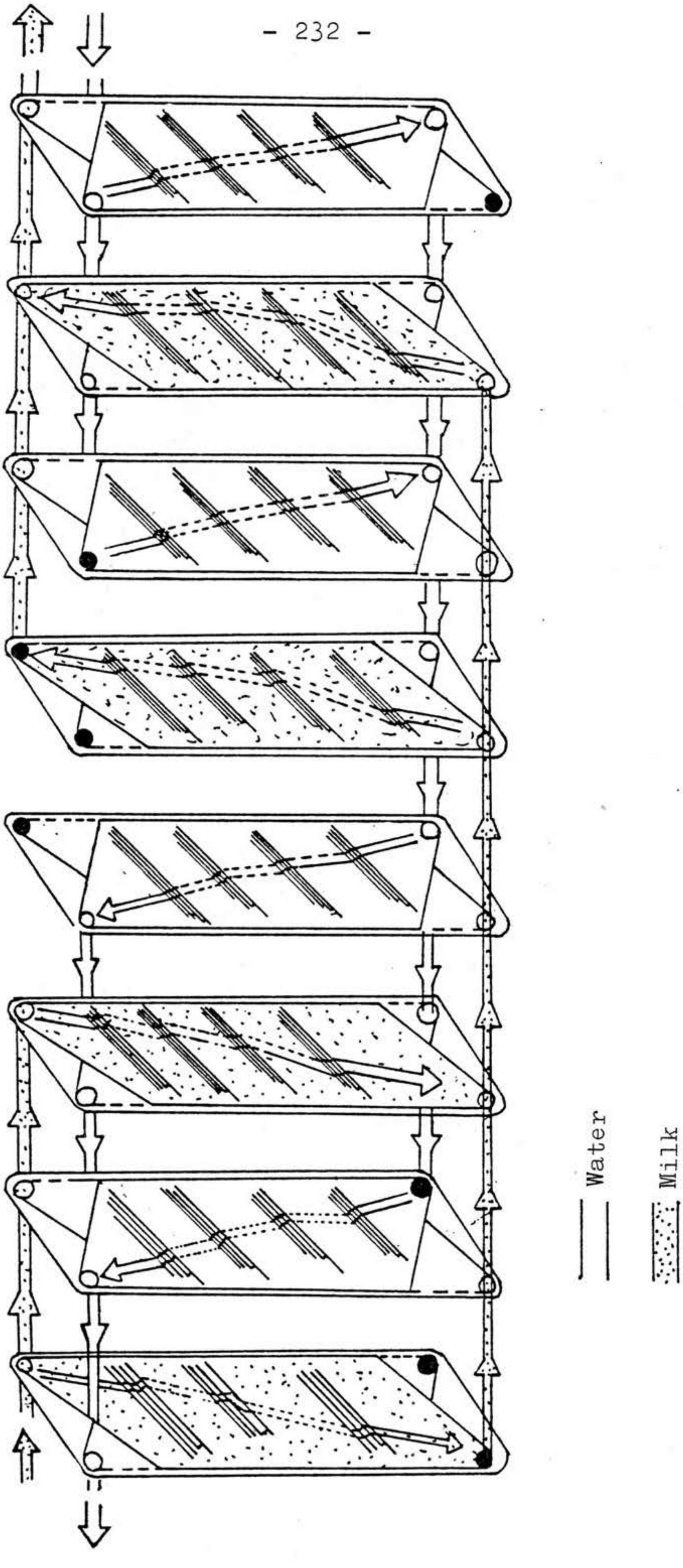

Figure 6.2 Fluid Flow in Plate Heat-exchanger

No labour is directly associated with the cooling operation. The milk from the dump tank (in can operations) or from the intake line (for bulk deliveries) is pumped through the cooler to the storage tanks and no direct-manning of the cooler is required.

The energy required for cooling the product is computed on the basis of the heat units to be removed, using the principles explained in Chapter 5. The refrigeration requirements for the two main reception alternatives (can, tanker) can be computed. The refrigerant (ammonia, freon, etc.) is usually circulated in a closed system and the cost per 1,000 gallons of milk cooled is negligible.

The main physical factors used with the cooler, therefore, are capital funds and energy, the extent of their use being determined by the temperature of the input and the intake rate

b) Storage

The insulated tanks in which the milk is stored temporarily between intake and pasteurization, come in a variety of capacities from 200 gallons to about 30,000 gallons. The tanks used for buffer storage inside the plant are mainly of the horizontal type with capacities at the smaller end of the range (200 gallons to about 7,000 gallons). Larger storage requirements are met by the use of silo tanks which are usually situated outside the buildings and range in capacity from 6,000 gallons to about 30,000 gallons. These tanks are pictured in Figures 6.3(a) and 6.3(b).

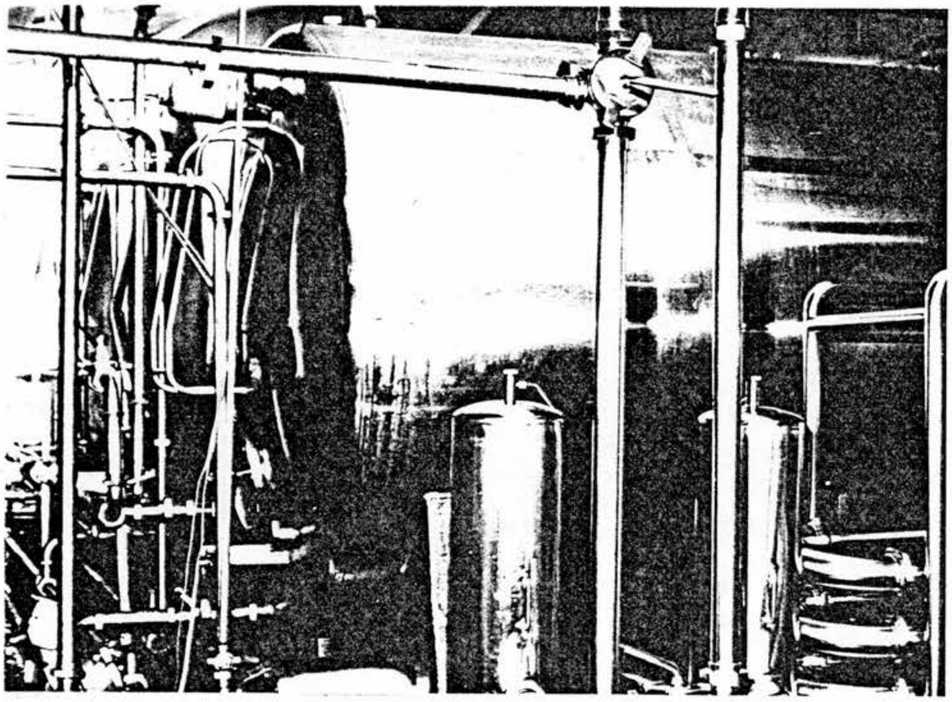

Figure 6.3 (a) Horizontal Storage Tanks

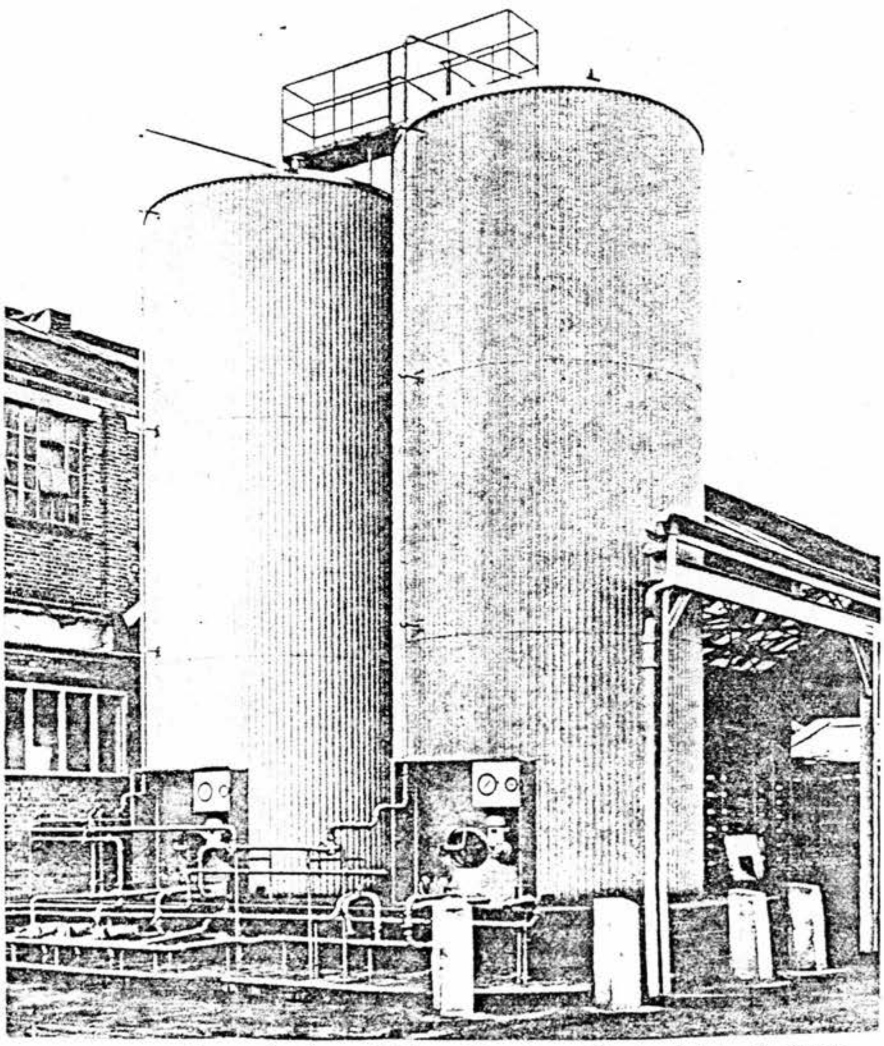

Figure 6.3 (b) Silo Tanks Outside Dairy

The choice at the storage stage of the process is not a choice from among alternative technologies *per se*. Rather, it is a choice of buffer storage capacity, which must be based on choices made at the initial reception stage *and* at the pasteurization stage. The capacity of the tank represents i) a period of storage required in the event of a plant breakdown, and ii) an additional capacity required to even out flow rates on either side of the buffer tank.

The general practice is to have a basic storage capacity corresponding to a maximum of 1½ hours of intake[1], to insure against breakdowns, when the rate of intake and of pasteurization is the same and the processing is continuous. However, where these rates are different and where pasteurization is by batch rather than continuous methods the storage requirement is increased. The storage capacity required for smoothing out fluctuations on either or both sides of a buffer storage or surge tank is discussed in greater detail in the following chapter, in relation to overall plant optimization.

The storage tanks are generally of double-walled construction with a layer of insulating meterial in between. The inner and outer walls are usually of stainless steel, although in many cases the outer may be of mild painted steel. The tanks come fitted with agitators which gently stir the milk to prevent the cream from separating from the milk under the influence of gravity while the milk is in storage. As with most plant equipment the cost of the storage tanks increases less than proportionately with their capacity.

As with the cooler, no labour is directly attached to the

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1 *Op. cit.* (p. 52).

storage operation. The tanks are not usually refrigerated and the only energy required relates only to the motor horsepower of the agitator. This requirement is small and manufacturers indicate that a $^1/8$ hp motor (0.093 kw per hour of storage) is all that is required.

In the economic evaluation at the plant level, the storage costs must therefore be related to the decisions made on either side of the storage divide.

6.2 Central Processing Alternatives

The central processing operations are those which centre around pasteurization and are mainly the conversion and preservation operations described in Chapter 3. As with reception, several operations tend to be grouped together as a unit or module. For these, separate equipment systems and methods may be identified as alternative technologies. This grouping facilitates the study of factor alternatives by avoiding the unnecessary complexities involved in the consideration of unrealistic and incompatible combinations of system components.

The central processing activities, therefore, are viewed as a dichotomy. The first class consists of those operations which centre directly around pasteurization. These are: the preservation operations of pre-heating, pasteurization and cooling after pasteurization, along with the conversion operations of filtering (or clarifying) and homogenization (where desired). The second class is the buffer storage operation which comes between pasteurization and filling of the product.

6.2.1 Pasteurization Alternatives

Two major alternative systems of pasteurization are considered. These are a) the vat (or batch) alternative and b) the modern regenerative continuous High-Temperature-Short-Time (H.T.S.T.) alternative. The lower temperature continuous process is rulled out by suppliers because it consumes more of all the factors than does the H.T.S.T. technology which superseded it.

a) Vat or Batch Pasteurization

This is sometimes described as the "long-hold" method of pasteurization which involves heating the milk to a temperature of 145°F (62.8°C) and holding it at this temperature for at least thirty minutes. This is an older vintage method and no heat regeneration is involved.

In a typical batch pasteurization system, the raw milk from storage is pumped through a tubular or plate heat exchanger for preheating to a temperature of 90-95°F (32.2-35°C) to facilitate the conversion operation of filtering or clarifying which is done before the full high heat of pasteurization is applied. The milk then flows into the pasteurizing vat where it is heated, held and then cooled. Finally, it is passed through a heat-exchanger (usually of the plate or tube type) to be cooled to the temperature required for buffer storage (40°F).

i) Physical plant

The basic plant components are: the heat exchangers for heating and cooling; the filter (including pump) and the pasteurizing vat. The basic cost of the vat is low but because of the considered need for additional heat exchangers, the physical plant requirement is substantially increased.

For vat pasteurization, the spray vat pasteurizer described in Chapter 3 (3.3.3(a)) is the type that tends to be favoured[1]. Electrically heated vats (immersion heaters) are also used. Typical capacities of pasteurizing vats range from 25 gallons to 300 gallons. Figure 6.4 illustrates the features of the spray vat.

One man is required to control the process, irrespective of the capacity of the vat, and the man is required for the total elapsed time of the process.

There is no regenerative heating and so energy requirements are high relative to those for H.T.S.T. pasteurization. The energy consumption is measured in terms of the heat units to be added (in Btu's) in the preheater and in the vat and those to removed in the cooler. The capacity of the boiler (boiler Hp) and the tons of refrigerant are then determined. Energy is also required for pumping.

Table 6.3 shows factor use by the vat system and the alternative H.T.S.T. system.

b) High-Temperature-Short-Time Pasteurization

Unlike the vat system, the High-Temperature-Short-time (H.T.S.T.) pasteurization system consists of a single piece of equipment in which the preheating, filtering, pasteurizing and cooling sequence is carried out. The filtering is done after the initial preheating[2]. Where the option to homogenize

1 See Harper & Hall (1976, p. 493).

TABLE 6.3

PHYSICAL FACTOR REQUIREMENTS FOR V.A.T. AND H.T.S.T. PASTEURIZER SYSTEMS

SYSTEM CAPACITY	INITIAL OUTLAY (£'000)	ELECTRICITY (KW RATING)	LABOUR (MEN FOR T.E.T)	INITIAL STEAM ('000 LBS.)	STEAM ('000 LBS/HR.)	FLOOR SPACE ('000 SQ.FT.)
A. V.A.T. PASTEURIZER (BATCH)						
25	12.4	3.3	2	--	0.04	0.05
50	12.4	3.3	2	--	0.08	0.05
100	12.8	3.3	2	--	0.15	0.08
200	13.4	3.3	2	--	0.30	0.10
300	14.6	3.3	2	--	0.45	0.14
B. H.T.S.T. PASTEURIZER						
50	13.48	2.2	0.5	0.01	0.01	0.13
100	13.98	2.2	0.5	0.01	0.02	0.13
200	21.90	4.5	0.5	0.02	0.04	0.24
500	23.69	4.5	0.5	0.06	0.11	0.24
800	24.98	4.5	0.5	0.10	0.11	0.24
1,000	32.92	12.5	0.5	0.12	0.21	0.54
2,000	38.72	15.2	0.5	0.24	0.42	1.43
3,000	40.92	15.2	0.5	0.37	0.64	1.43
5,000	46.22	14.4	0.5	0.61	1.07	1.43
8,000	55.92	20.6	0.5	0.98	1.71	1.43

NOTES:

1. FOR BATCH THE SYSTEM CAPACITY IS THE VOLUME OF THE VAT. .
   FOR HTST IT IS THE THROUGHPUT RATE PER HOUR (TECHNICAL CAPACITY).

2. SEE NOTE 3, TABLE 6.1 FOR BATCH THE INITIAL OUTLAY INCLUDES COST OF PLATE PREHEATER AND PLATE COOLER.

3. SEE NOTE 3, TABLE 6.1

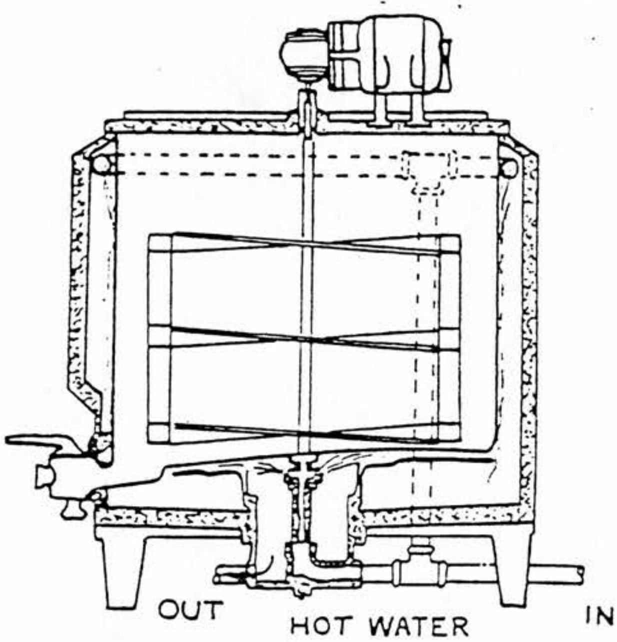

Figure 6.4 The Vat (batch) Pasteurizer - Spray vat type

is taken, the milk is, at this point, pumped through a homogenizer and returned to the pasteurizer to continue the heat treatment.

In the modern H.T.S.T. system being considered the preheating and initial cooling are done by milk-to-milk regenerative heat exchange. The unit therefore incorporates a regenerative section where the incoming cold milk cools the outgoing milk from the pasteurization section and is itself preheated by the hot milk. The units being considered are 90 percent regenerative. Heating and cooling media are required for the high heat pasteurization section and for the final stage of the cooling to take the product down to the $40^{\circ}F$ ($4^{\circ}C$) necessary for storage.

The H.T.S.T. pasteurization requires a minimum of $161^{\circ}F$ ($71.7^{\circ}C$) for at least 15 seconds (see Chapter 3 (3.1.1a)). The unit, therefore, incorporates a holding section which is, in most cases, an external cell in which no heating or cooling takes place. The milk simply flows through a passage. The length of the passage and the rate of the flow are calculated so that the through flow time in the holding cell is equal to the required hold. This external cell usually consists of a length of piping arranged in a spiral or zig-zag pattern. A typical H.T.S.T. regenerative unit with in-line filter and external holding cell as described above, is illustrated schematically in Figure 6.5(a). Figure 6.5(b) shows a similar pasteurizer in a processing plant.

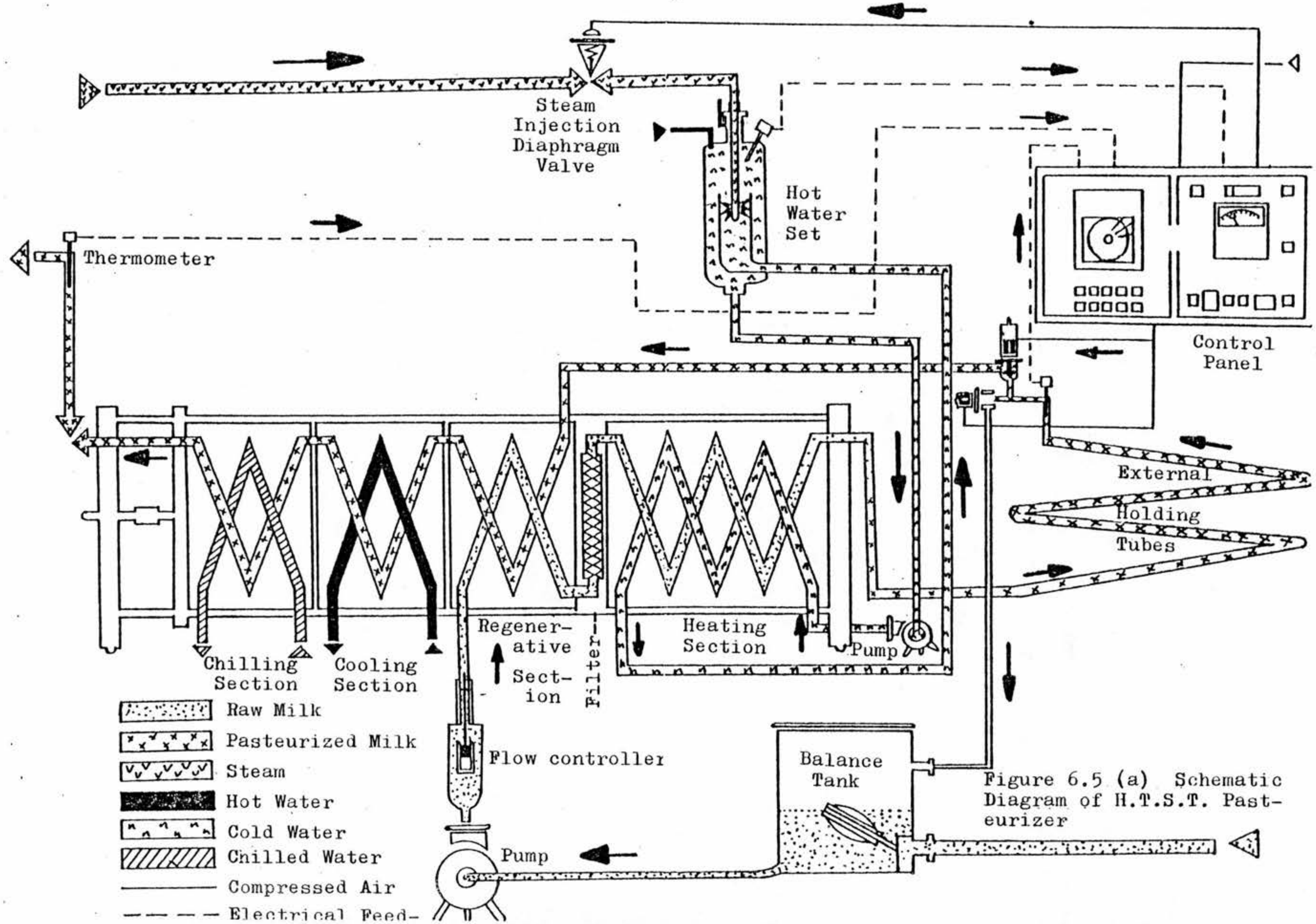

Figure 6.5 (a) Schematic Diagram of H.T.S.T. Pasteurizer

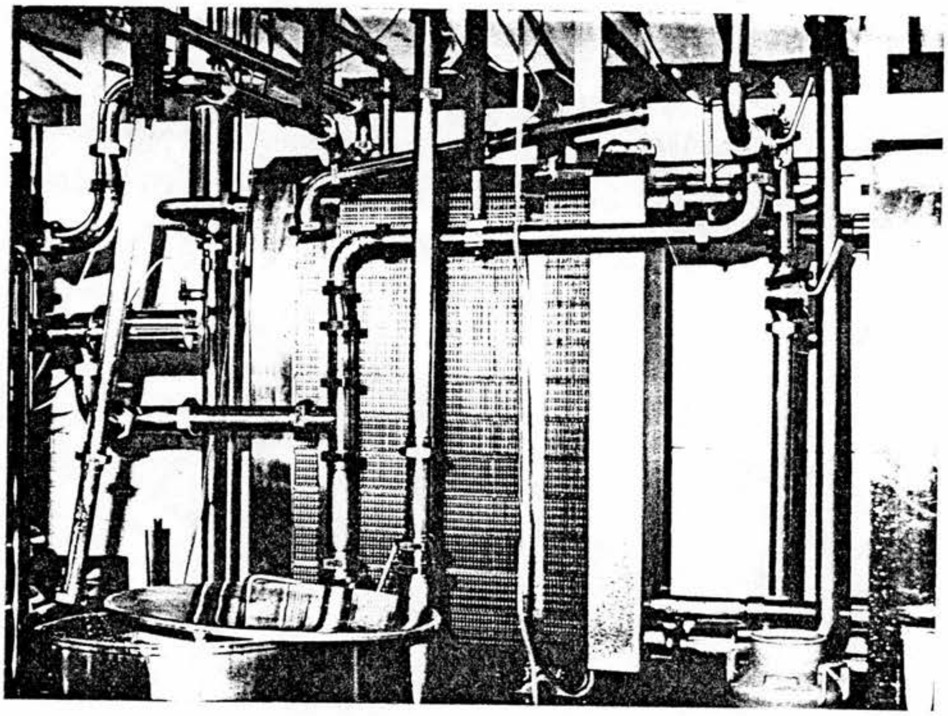

Figure 6.5 (b) H.T.S.T. Pasteurizer
in Dairy Plant
(Courtesy of Edinburgh Daries)

Physical plant

The H.T.S.T. unit is sold, usually, as a complete system with the filter, necessary pumps and pipework included. One feature of the system is that the process is automatically controlled. This means that instruments for process control are required. These are also included with the basic unit. The initial costs used for this study also include the cost of the air compressor required for the operation of the instruments. Data on the physical factors are provided in table 6.3.

The H.T.S.T. unit is estimated by the manufacturers to have a useful life of 12 years with a scrap value of 3% of initial cost in real terms. The average annual cost of spare parts is estimated at 2.5 percent of the initial cost in real terms. An average of 40 man hours of maintenance is estimated to be required annually, this being largely attributable to the maintenance of the instruments, controls and electrics.

(i) Labour

The H.T.S.T. operation is fully automatic and so, unlike the vat system, does not require constant manning while in operation. Periodic checks would, however, be required and, during visits made to dairies, the author observed that a worker's attention was required for approximately 25 percent of the total elapsed time for the pasteurization process.

(ii) Energy

With 90 percent regenerative heat exchange, the milk entering the pasteurizer at 40°F (4°C) requires to be heated by $121^{\circ}F$ ($67.7^{\circ}C$) to reach $161^{\circ}F$ ($71.7^{\circ}C$) before being held for 15 seconds and can be heated to $149^{\circ}F$ ($64.9^{\circ}C$) by regeneration. Only a further $12^{\circ}F$ (or $6.8^{\circ}C$) remains to be added by the heating medium used with the plant. This additional heat is usually provided by steam. Manufacturers provide data on the steam consumption of the various units of different capacities, from which boiler Hp and the quantity of primary fuel required can be computed.

In addition, after being heated to pasteurization temperature, the product is cooled regeneratively. The remaining heat units are removed using chilled water.

Data on the motor Hp required for pumping milk through the system and for the air compressor are provided by the manufacturers.

6.2.2 Buffer Storage

The decision on buffer storage capacity between pasteurization and filling, is again dependent on the rates and types of inflow and outflow, in addition to the insurance against breakdown factor (see Section 6.1.2).

Where vat pasteurization is chosen there is a pulsed (batch) input to be stored for output to a continuous filling operation, which further complicates the decision-making process. This is dealt with in more detail in the following chapter.

The tank capacities and characteristics are the same as have been described in Section 6.1.2.

6.3 Filling and Casing Alternatives

The filling of a product into containers is listed under preservation operations, while casing is included among auxiliary operations. However, because of the closeness with which these operations are performed in the dairy they are given joint consideration. In the case of filling into glass bottles, the washing (cleaning) operation on the bottles is included here as well, in order to give proper balance to the evaluation of that alternative in relation to the others.

The three basic alternatives to be considered are: (1) bottling in glass, (2) bottling in plastic bottles and (3) filling in paper cartons. The filling operations are all largely mechanical with relatively little choice for factor substitution. With bottle washing the alternatives are less restricted. Casing, as is typical of most auxiliary operations, allows a greater scope for choice between manual and mechanical methods. Casing options are examined for each of the three filling alternatives in turn.

For filling into plastic bottles, account must be taken of the actual manufacture of the bottle itself in the plant, since the bottle manufacture is an inplant operation. For the other alternatives, the containers are bought in from other manufacturers. These costs are also taken into account. Comparative factor use by the three respective alternatives are examined in Table 6.4.

6.3.1 Filling and casing of Glass Bottles

Bottles are uncased and washed immediately prior to filling. After filling the filled bottles are cased (manually

TABLE 6.4 (TO BE CONT'D)

PHYSICAL FACTOR REQUIREMENTS FOR ALTERNATIVE FILLING SYSTEMS

SYSTEM	INITIAL OUTLAY						ELECTRICITY						LABOUR					
CAPACITY	(£'000)						(KW RATING)						(MEN FOR T.E.T)					
(GALS./HR.)	GB1	GB2	GB3	PB	CT1	CT2	GB1	GB2	GB3	PB	CT1	CT2	GB1	GB2	GB3	PB	CT3	CT2
225	53.0	57.8	93.4	100	38	73.0	2.8	8.2	10.4	36	10.0	12.0	4	2	1.25	3	1	1
450	64.0	68.8	93.4	150	45	95.0	4.5	9.2	10.4	51	11.7	13.7	5	2	1.25	3	2	1
600	79.5	83.3	121.4	210	80	160.0	5.4	11.2	16.2	69	13.3	17.3	7	3	1.25	5	2	1
900	90.5	93.8	152.0	266	92	205.0	7.3	14.2	19.3	85	22.5	25.8	10	5	1.25	6	3	1
1200	102.6	106.1	181.0	292	160	235.4	9.4	20.0	31.0	100	30.5	31.5	12	5	1.25	6	3	1
1500	128.1	130.6	181.0	333	184	266.7	13.1	22.5	31.0	125	55.6	39.0	15	6	1.25	7	6	1
2200	164.1	164.6	208.3	383	276	334.7	18.4	28.5	36.6	185	78.4	44.0	21	8	1.25	8	9	1
3000	222.0	221.8	222.5	453	388	393.2	21.8	42.0	46.1	228	95.2	49.0	27	10	1.25	9	12	1
3700	326.0	225.5	282.7	493	460	445.6	26.0	49.0	59.2	289	104.0	56.0	34	13	1.25	10	15	1
4500	382.5	382.0	318.7	502	525	490.4	30.3	56.0	67.2	350	135.0	65.0	40	15	1.25	11	18	1

TABLE 6.4 (CONT'D)

PHYSICAL FACTOR REQUIREMENTS FOR ALTERNATIVE FILLING SYSTEMS

SYSTEM	STEAM						WATER						GAS						FLOOR SPACE					
CAPACITY	('000 LBS/HR)						('000 GALS/HR)						('000 CU FT/HR)						('000 SQ FT)					
(GALS/HR)	GB1	GB2	GB3	PB	CT1	CT2	GB1	GB2	GB3	PB	CT1	CT2	GB1	GB2	GB3	PB	CT1	CT2	GB1	GB2	GB3	PB	CT1	CT2
225	0.13	0.25	0.36	--	--	--	0.33	0.48	0.57	1.90	0.05	0.04	--	--	--	--	0.01	0.01	0.44	0.47	0.63	0.48	0.20	0.43
450	0.28	0.36	0.36	--	--	--	0.45	0.57	0.57	3.50	0.08	0.08	--	--	--	--	0.05	0.06	0.67	0.60	0.72	0.68	0.26	0.57
600	0.36	0.43	0 58	--	--	--	0.48	0.57	0.67	4.50	0.08	0.08	--	--	--	--	0.12	0.12	0.46	0.79	1.38	1.03	0.25	0.62
900	0.56	0.60	0.63	--	--	--	0.68	0.73	0.88	6.50	0.13	0.13	--	--	--	--	0.23	0.18	1.23	0.96	1.38	1.43	0.45	0.81
1,200	0.62	0.69	0.73	--	--	--	0.90	1.12	1.39	7.50	0.17	0.17	--	--	--	--	0.24	0.23	1.73	1.26	1.81	1.78	0.72	0.98
1,500	0.91	0.95	0.73	--	--	--	1.25	1.42	1.39	8.50	0.19	0.21	--	--	--	--	0.40	0.29	2.17	1,50	1.81	2.09	0.90	1.04
2,200	1.13	1.09	0.87	--	--	--	1.73	1.80	1.54	10.00	0.26	0.30	--	--	--	--	0.48	0.39	2.84	1.82	2.08	2.33	1.05	1.16
3,000	1.51	1.61	1.15	--	--	--	2.29	2.44	2.02	12.60	0.34	0.37	--	--	--	--	0.80	0.44	3.60	2.32	2.45	2.60	1.18	1.24
3,700	1.82	1.85	1.34	--	--	--	2.75	2.79	2.45	13.50	0.41	0.45	--	--	--	--	0.87	0.49	4.46	2.78	2.81	2.95	1.24	1.31
4,500	2.15	2.21	1.47	--	--	--	3.27	3.30	2.74	14.20	0.51	0.50	--	--	--	--	1.00	0.53	5.42	3.27	2.31	3.30	1.36	1.40

NOTES

1. THE FILLING SYSTEMS ARE DESCRIBED IN SECTIONS 6.3 AND 7.2
2. SEE NOTE 2, TABLE 6.1
3. SEE NOTE 3, TABLE 6.1
4. SEE NOTE 4, TABLE 6.1

or automatically) and are stacked and taken to storage.

a) Washing of glass bottles and cases

After being uncased, the bottles are washed, and proceed directly from the washer to the filler. The cases are washed separately. The washing and filling operations must therefore be synchronized.

Bottle washing technologies may be considered as manual, manually assisted, and fully automated. The washing of bottles in a purely manual operation is not considered a feasible alternative in all except a cottage scale production unit. In a larger plant, where a constant flow of clean bottles is required for the smooth operation of the filling equipment, a manual washing system could present scheduling difficulties.

i) Manually assisted bottle washing

Manually assisted washing of bottles involves the use of a "come back" type of washer where the bottles enter and return in the same place. One worker is required to feed the bottles into the machine for washing rates under 100 bottles per minute, and must attend to the operation for the total elapsed time of the washing operation. The machine capacities typically range from 60 to 160 bottles per minute. At rates over 100 bottles per minute, two workers are required for the operation.

Most washers combine soaking with jet action cleaning. The bottles may pass through as many as fifteen or more stages where they are either soaked or jetted with water and detergents. Motor energy is required for moving the bottles through the washer and for pumping in the jet stages. Thermal energy is required for heating the water and for providing steam.

The cases are washed separately as they pass on a conveyor under sprays of water and detergent. No labour is required for this part of the washing operation. Motor energy is required for powering the conveyor and thermal energy for heating the water used in the process.

In a fully automatic washing operation the "straight-through" type of bottle washer is used. The bottles are placed on a conveyor, picked up mechanically, and fed into the washer. After passing through the washing and sanitizing sequences, they emerge at the other end on their way to the bottle filler. Figure 6.6(a) shows bottles being mechanically picked up by suction cups off a conveyor to be fed into an automatic machine. The cases are diverted to pass through the case washing tunnel.

Although the process is automatic a worker is usually required to supervise the operation on either end. These workers can also be performing other jobs related to the bottling process and so their labour hours should not be allocated to the washing equipment for the full elapsed time of the washing. Where bottles are uncased manually, the worker uncasing the bottles and placing them on the washer conveyor would be at the entrance end of the washer. The worker on the exit side of the washer would also be keeping vigil on the bottling operations, with automatic bottling operation. All four operations (uncasing, washing, filling, casing) must be considered together for a proper analysis of labour requirements.

ii) Filling and casing of bottles

The bottle filling operation is largely machine paced. The internal conveying system central to the filler takes the bottles to the filling nozzles where the filling is done mainly by use of a vacuum method which prevents broken bottles from being filled. No assistance from labour is usually required as the actual filling is an automatic process. Some supervisory attention is required to ensure that the process is running smoothly.

The cost figure of the bottling system quoted by manufacturers includes the component parts of the machine, including the bowl which holds the milk, the vacuum pump, the internal conveyor system and the necessary piping for the system.

Energy use for the system is associated with the requirements for motor energy and for air compression for capping the bottles with foil.

The bottles leaving the automatic filler may then be packed into cases manually or with the use of a bottle caser. For automatic casing, the bottles are picked up off a conveyor by the suction cups of a casing machine and placed into cases to be conveyed to the stacking area. Figure 6.6(b) shows bottles being picked up by a casing machine. Manual casing by two workers is considered up to about 70 bottles per minute coming from the filler. Most available bottle fillers are above this size and require automatic casing.

Slower speed carton fillers were found to be more widely available, allowing greater scope for manual casing. In visits to dairies, it was often found that cartons were cased

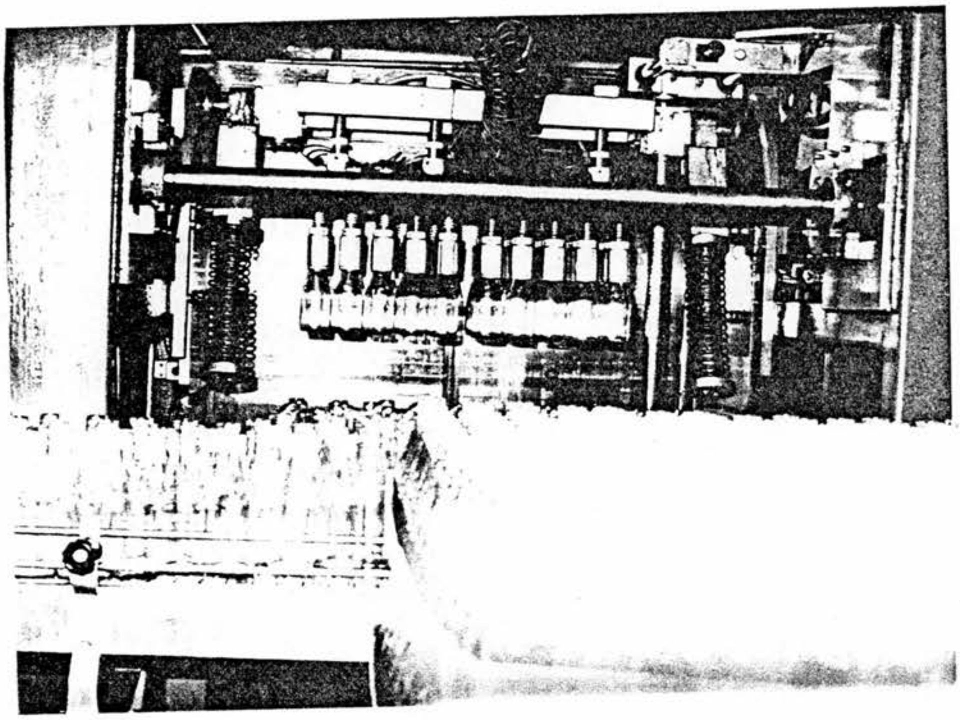

Figure 6.6 (a) Automatic Bottle Washing - Bottles Picked up by Suction Cups and Fed into Washer (Courtesy of Edinburgh Dairies)

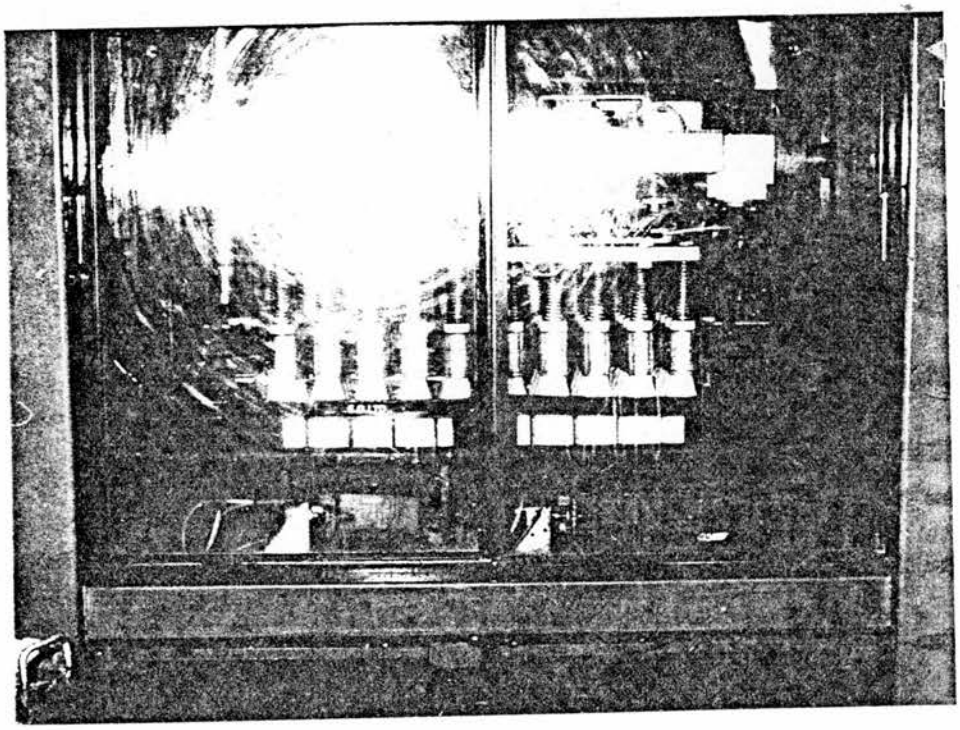

Figure 6.6 (b) Automatic Bottle Casing - Bottles Placed in Cases on Moving Conveyor (Courtesy of Edinburgh Dairies)

automatically. This affects the relative use of physical factors of production (see Table 6.4).

6.3.2 Filling and Casing of Plastic Bottles

The filling of milk into plastic bottles requires, in the first place, the plant equipment for the manufacture of the bottles inside the dairy. The bottles made from melted granules of a plastic (P.V.C.). The formed bottles are then transferred pneumatically to the filling point.

One worker is required to ensure the bottles are in an upright position as they are blown on to the filling conveyor. Because of the light weight of the bottles another worker is usually required to ensure the bottles reach the filling nozzle while still in an upright position.

Thus, as with glass bottle filling, a greater quantity of physical factors are usually required in the plant, because of the other operations which must be performed in the plant (glass-washing, plastic-manufacture) in addition to the filling. Comparative details of factor requirements for the three bottling systems are given in Table 6.4.

The casing of plastic bottles is usually done manually because of the soft plastic material of the bottle, which is unsuited to machine handling. The number of workers required for casing depends on the filling rate. Two workers are generally used for operations over 70 bottles per minute. Figure 6.7(b) shows the manual casing of plastic bottles.

The figures given for plant costs include the manufacture of the bottles and their filling. Energy data include the energy for the manufacture, transfer and filling of the bottles.

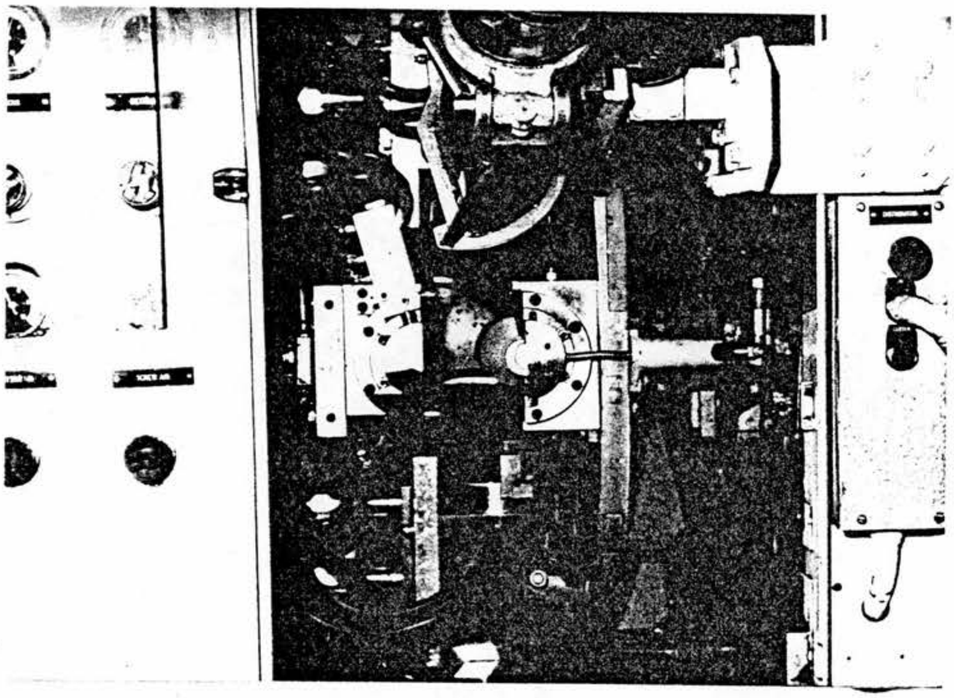

Figure 6.7 (a) Plastic Bottles Being Manufactured in Dairy Plant.

Figure 6.7 (b) Plastic Bottle Filling and Casing

(Photographs Courtesy of Edinburgh Dairies)

6.3.3 Filling and casing of cartons

No washing operations are associated with the choice of carton filling. The cartons are fully disposable. The filling operation is mechanical and the casing may be done manually or mechanically. Comparatively fewer physical production factors are used in the plant (see Table 6.4).

a) Filling of cartons

The equipment used for the filling of cartons is usually of the form-fill-seal type. The cartons are delivered to the plant as flattened "blanks", with flexigraphic printing of the dairy's design, having been cut, creased and sealed longitudinally. The carton is made of paperboard with a coating of polythene which also acts as an adhesive.

The flattened "blanks" are fed into the machine. They are opened, pressed and heat sealed at the bottom. They then pass under the filler nozzle where they are filled and then conveyed past overhead heating where a moving jaw seals the top of the carton. They are cooled and conveyed to the point of casing.

The equipment is available in capacities ranging from about 32 cartons per minute to over 160 cartons per minute. The machine, regardless of capacity, requires one man to attend to the feeding of blanks and to ensure that the filling and sealing operations are being satisfactorily performed. With filling speeds at the lower end of the scale (35-40 bottles/min.) one worker can do the casing and the filling of blanks, where casing is done manually. Above this speed a separate caser is needed for manual casing.

For high speed filling more than one caser is required. The high speed filling equipment (180 cartons/min.) is obtainable with two separate lines and one caser is stationed at each line for the full total elapsed time of the filling operation. Figure 6.8 shows the manual casing operation.

With mechanical casing no labour hours are attached to the casing operation.

Energy is required for driving the internal conveying system of the filling machine, for air compressors and vacuum pumps. Further energy is required for the automatic casing equipment. Thermal energy is required for the heat sealing operation (gas is often used as the primary fuel).

6.4 Auxiliary Operations

The auxiliary operations considered in this section are (1) Stacking of cases and (2) loading out of cases. These operations, as is typical of auxiliary operations, allow a reasonable choice between manual and mechanical methods.

6.4.1 Stacking of cases

The filled cases may be stacked mechanically by installation of a pneumatically operated case stacker. The stacking equipment operates at rates between 20 and 35 cases per minute (240-420 bottles/min.). No constant worker supervision is required and so labour requirements are low in comparison with the manual alternative. With this system energy consumption is low as energy is required only for the air compressor for the pneumatic operation.

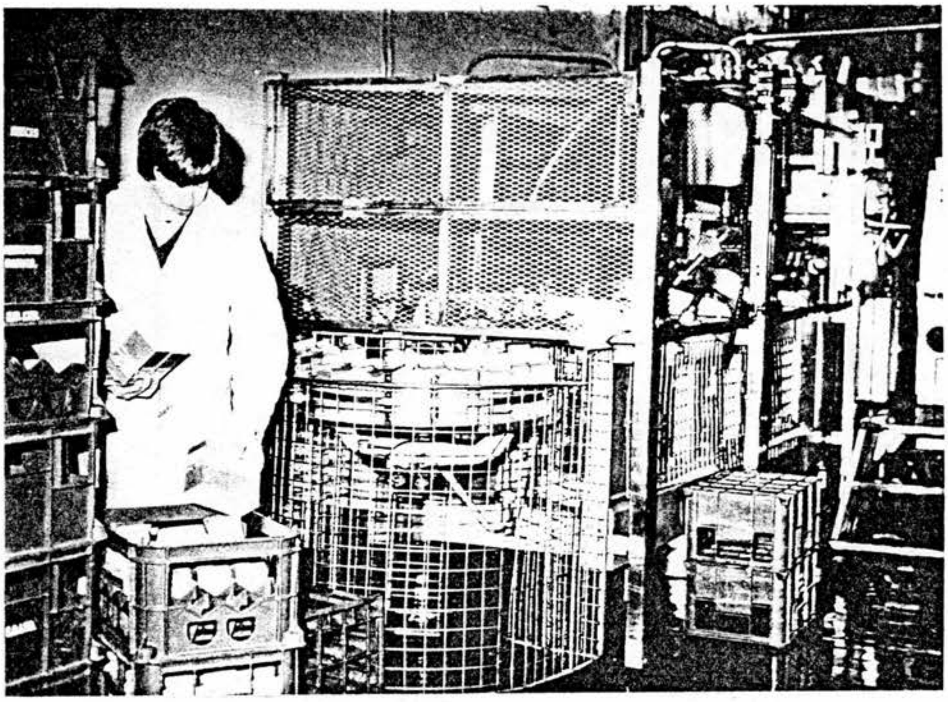

Figure 6.8 Manual Casing of Cartons
(Courtesy of Edinburgh Dairies)

The stacked cases are then conveyed to storage on some type of fork lift truck. One driver is used per truck and one truck can handle a stacking line. The operation of the fork lift truck is paced by the operation of the stacking machine.

For manual stacking a two-wheel case trolley[1] may be used. One stacking worker is required for every one casing worker where manual casing is involved, for casing of cases or bottles up to approximately 100 bottles per minute. The labour time attributed to the stacking (as well as the casing) operation is based on the operating time of the machine, and therefore depends on the machine rate and the quantity of milk being processed.

No energy or other utility requirements are attached to the manual stacking operation.

6.4.2 Loading operations

Cases are conveyed out from storage to the delivery truck usually in much the same way as they were taken into storage. The operation is usually paced by the rate at which the delivery truck personnel can handle the loading. With a fork lift truck, the cases are lifted mechanically and placed on the delivery truck. One man operates the fork lift and elapsed time for loading is therefore much reduced on the manual operation.

Alternatively, the two-wheel case trolley may be used.

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1 A case trolley is a simple piece of equipment with two rubber wheels and a metal frame on which cases are stacked. The cases can then be wheeled into storage or to the loading out dock.

One worker is usually involved in the loading of each truck. An allowance of twenty cases loaded in 15 minutes appears from observation to be reasonable. With the fork lift truck this period would be reduced by approximately 50 percent.

In this aspect of processing where the operation is no longer machine paced or directly related to other activities, the quantification of the factor input use (factor time) in relation to output is subject to much uncertainty. The figures used (as with manual can reception) must be regarded as approximate.

The physical factor requirements can be estimated in relation to specific input quantities for each group of operations described in this chapter. A comparison of the relative use of different factor inputs by the various technological alternatives is useful where the emphasis is on making the greatest use of the physical factors of production which are considered to be the more abundant in any given country or economic situation.

However, with several inputs being considered (physical plant, labour, energy, other utilities), the weighing of one alternative against the other becomes a fairly complicated process. To avoid this, monetary values are attached to the factors for their evaluation. The actual factor prices used may be chosen to reflect prevailing market prices in any economy, or to represent some conception of the social price structure for an economy.

In the following chapter, this economic evaluation of the alternatives is done and the comparative analysis is advanced from the level of individual .perations (or groups of operations) to the plant level by use of the technique of Dynamic Programming.

CHAPTER 7

THE ECONOMIC CHOICES

In the final analysis, the alternatives must be compared by attaching economic values to the physical factors so that the appropriate economic decisions may be made about the selection of alternatives in any economic context. Because of the inclusion of extra factors in the physical set instead of considering only capital and labour, comparison of the alternatives requires even more that they be expressed in a common unit.

In this chapter, the first section is concerned with the methods of evaluation of the alternative physical combinations of factors. The methods proposed are by no means the only or the most widely acceptable. The flexibility built into the design of the optimization technique allows many other forms of evaluation to be tried and compared.

Section 2 focusses directly on the economic choices at the individual stage level, based on the physical factor quantities identified in Chapter 6. In deriving the cost relationships, the prices attached are intended to represent hypothetical economic cases, and are designed to show extreme situations and how they affect the functions and the choices that could be made.

The plant level optimization procedure is discussed in Chapter 3. In the FORTRAN coded programme, the input data described in real terms are entered and costed using different factor price ratios. This section demonstrates the application of the Dynamic programming technique for plant level optimization, which obviates the necessity of either assuming that the stage decisions are independent, or of evaluating and comparing at the plant level all the possible sub-process combinations.

7.1 The Economic Evaluation of Alternatives

The Economic values attached to the alternatives are more appropriately labelled "Investment costs" and "operating costs" in lieu of the traditional capital cost-labour cost dichotomy. Thus, investment costs are attached to the physical factors, the acquisition of which requires access to investment funds. The term operating cost is preferred since it encompasses those costs attached to the energy and "other utilities" variables in addition to the labour variable where costs are assumed to be incurred and met during the day-to-day operation of the plant.

For this purpose, all the factors are considered variable because the cost curve to be constructed is a "planning" or ex-ante curve and is akin to the long-run curve of traditional economic theory. It is assumed that all the required factors are available. The two broad categories of cost are considered in turn.

7.1.1 Investment costs

These investment costs are associated with the use of

a) physical plant equipment or the "physical" capital variable and with b) the overall building requirements derived from the "floor space" variable. All investment costs are diurnalized.

a) <u>Physical Plant Equipment</u>

For the computation of daily investment or ownership cost of the plant equipment, the following data are required from the manufacturers:

i) the purchase price plus installation cost of the equipment, (P) (in 1980 values);

ii) the life of the equipment, ℓ (in years);

iii) the scrap value (or salvage value) of the equipment at the end of its useful life (ignoring inflation and using constant 1980 values, (SV);

iv) the annual value of spare parts.

The method of computation of the annual ownership charge must be decided with respect to i) depreciation and ii) interest.

i) <u>The annual depreciation and renewal charge</u>

Two methods of calculating the annual depreciation charge on plant equipment which are generally suggested are the Fixed Instalment or the Straight-Line Method and the Diminishing Balance Method, each with its relative merits and demerits with regard to the problem at hand.

By use of the diminishing balance (or double-declining) method the advantage is that a fairly even charge is made against revenue each year since the depreciation charge is heavier in the early years when repairs and maintenance are lighter and it is increased in the later years when repairs and maintenance charges increase. Using SV, P and ℓ as defined above a constant rate of depreciation r is applied annually to the declining balance using the formula

$$SV = P \left(\frac{100 - r}{100}\right)^{\ell} .$$

Cost studies of the nature considered here[1] have favoured the use of the straight-line method of depreciation which is generally more convenient for the purpose. The straight-line method is recommended by the Institute of Chartered Accountants for certain assets, including Freehold buildings, plant and machinery, tools and equipment which "are subject to depreciation by reason of their employment in the business."[2]

In using the straight line method, with a constant sum being written off each year, the cost of repair and replacement (spare parts), which is usually lower in the earlier years and higher in the later ones, might also be written off as a constant sum every year. In the survey, manufacturers have tended to give the cost of spare parts and repairs as a percentage of initial purchase price of the equipment, and as a figure for some average year neither at the beginning nor at the end of the equipment life. The cost study by Hall (1952) also used a constant value for repair costs, which are included under "fixed" costs.

The approach in this thesis is therefore to use the straight line depreciation method,

$$d = \frac{P - SV}{\ell}$$

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1 C.W. Hall (1952) and U.S. Dept. of Agriculture Marketing Report 232.

2 Garbutt (1969, p. 0622).

where d is the annual depreciation cost to be set aside as an investment or ownership cost. Added to this is the annual repair and maintenance cost, M, comprising the repair and depreciation cost R associated with having that equipment in use in the plant. Thus

$$R = d + M,$$

for a representative year in the life of the equipment.

ii) Interest charges

Interest charges are generally included on the basis that the money used to purchase the equipment could otherwise be employed for other purposes where it could earn a certain rate of interest. Interest at this given rate can be compounded annually over the life of the equipment and this sum and the asset are then together written down by equal annual instalments until the end of the period (life).

In this method, generally referred to as the Annuity System of depreciation[1], there is the combined charge being made for the replacement of the asset at the end of its economic life, and for the opportunity cost of having used the funds in this way.

Using the joint approach to asset replacement and interest charges, the amount to be written off annually by the annuity method (i.e. principal + interest- instalments) is calculated using the formula provided by Garbutt (1969)

$$D_A = P\left[\frac{i}{(1+i)^{\ell}-1} + i\right]$$

where i = the fixed rate of interest.

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1 *Op. cit.*, p. 0611.

Given that the asset has a known scrap value and therefore the whole value of the capital investment need not be recovered, it is suggested that instead of multiplying the recovery factor by P, the quantity $(P - SV)$ may be used.

Thus, in computing the annual ownership costs associated with plant equipment, the asset recovery cost, opportunity cost and cost for repair and replacement of spare parts may be obtained from the equation

$$O_E = D_A + M$$

where, O_E = Ownership costs associated with equipment (annual)

M = the renewal and replacement cost (annual) measured by the value of spare parts required.

One assumption implicit in the inclusion of M among ownership costs is that these repair costs are necessary as long as the equipment is selected and put to use in the processing plant.

b) Plant buildings

One engineering rule-of-thumb for computing the initial cost of the buildings for housing the plant equipment is to assess the cost of the buildings including services[1] as a certain percentage of the purchased-equipment cost, depending on the type of process plant (e.g. solid, solid-fluid, fluid). While this may be useful for comparing products and processes which are very different (e.g. fertilizer plant compared with brewery), it is less relevant to the situation in which

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1 See Peters & Timmerhaus (1968, p. 112).

alternative equipment systems and methods are being evaluated for the processing of a single product, where building materials, construction costs, and service requirements are unlikely to vary significantly with the cost of the alternative equipment systems. Special services attached to particular types of equipment systems (e.g. special plumbing etc.) are accounted for in the stated cost of the equipment, which, in this thesis, includes the installation cost.

It seems much more appropriate, therefore, to relate the cost of the buildings required to the floor space that is necessary for the equipment and its operators. Costs for the building may be expressed as cost per square foot of floor area and would therefore largely be determined by the material and labour costs in the country in which the building is being constructed. This gives some further leeway in assessing the costs of the alternatives in relation to varying economic environments.

It may be noted that no consideration is being given to the costs involved in site development and other such costs which bear little relation to the actual processing choices within the plant.

Thus the analysis will be conducted on the basis of a given cost per square foot of floor area compatible with the particular economic environment which is represented by the other factor costs being used at any given point in the analysis.

Depreciation and interest

Buildings are generally considered to depreciate much more slowly than plant equipment. There is usually no scrap value attached to the end of the economic life of buildings for processing. Indeed, it is sometimes felt that because of technological changes which take place over the long life of a plant building, the structure may be more of a liability than an asset at the end of the period of depreciation.

For a dairy processing plant building, an assumption of a life of fifty years is being made. Applying the formula for straight-line depreciation, the annual depreciation charge allowed would be

$$D_B = \frac{I_C}{\ell_B}$$

where D_B = annual depreciation charge for buildings

I_C = Initial cost of the buildings

ℓ_B = life of buildings = 50 years.

The rate of depreciation would therefore be 2.5 percent per year of the initial cost of the building.

Again it is possible to take into account the opportunity cost associated with the use of funds to purchase this type of asset rather than any other, and, therefore to attach some figure to represent the cost of capital services. Thus, the same method may be used as for equipment to determine the amount to be written off as a cost each year. Using the annuity method, this becomes

$$D_B = I_a\left[\frac{i}{(1+i)^{\ell_B}-1} + i\right]$$

where, as before, i = the chosen rate of interest.

No renewals and repair costs are considered for the buildings, as is essential with plant machinery and equipment which must be maintained in working order in a way that is not necessary for building structures.

The total annual investment cost attributable to a given equipment system is therefore

$$O_T = O_E + D_B$$

where O_T = Total ownership costs, or Investment costs (fixed)

O_E = Ownership costs associated with the equipment systems, such that $O_E = D_A + M$ (see section (a) above)

D_B = the ownership costs associated with the buildings.

These ownership costs, which represent the standard capital cost in the economic production function, then must be diurnalized. To do this an assumption must be made about the number of working days in a year, so that daily costs can be imputed to the alternative equipment systems. Typically a dairy operates six days per week thereby having an annual operation of 312 days.

Unit costs are therefore computed on the basis of the daily throughput volume and are based on units of 1,000 gallons.

7.1.2 Production or operating costs

The costs directly associated with the operation of the plant equipment are those occasioned by the use of a) labour, b) energy and c) other utilities.

a) Labour costs

Once the "physical" labour variable is evaluated it can simply be multiplied by the appropriate wage rate. The physical variable would be expressed in terms of man-hours required for processing a given daily quantity of the product. An hourly wage rate can then be applied to this figure.

The unit labour cost (cost/1,000 gals.) may be computed for the specific equipment system and daily throughput volume. Alternatively, to avoid the use of very small fractions and the associated rounding errors, it may be preferable to compute unit costs for all the operating factors together. Unit costs may also be left to be computed at the overall plant level for a given input quantity, to give the lowest total unit costs after optimization.

b) Energy costs

There are two physical variables from which energy costs may be derived, the first of which is the Electrical energy unit, the kilowatt-hour (Kwh), deduced from the horse-power (hp) requirements and kVA ratings of equipment, as discussed in Chapter 6. The second relates to the fossil or primary fuel requirement (coal, oil, gas) associated mainly with the British Thermal units (Btu) necessary for the production of steam and/or hot water.

An appropriate electricity tariff can then be attached to the Kwh requirement and the charge for the primary fuel units used to convert these physical quantities to cost values. It is also possible to convert the boiler Btu to Kwh and combine with the other Kwh requirement so that a single tariff may be applied. The cost of the primary fuel is usually lower than the cost of electricity and the relative advantages of the different energy sources can be evaluated for the respective economic environments being considered in the analysis.

Energy is also required for the production of compressed air and the compressor hp must also be taken into account and converted to Kwh to be multiplied by the electricity tariff.

c) Other utilities

The principal item to be evaluated under other utilities is the cost of water. The physical quantity of water used in connection with the equipment system is simply multiplied by the water tariff.

The other utilities are largely associated with energy consumption (electricity, fuel) and are evaluated under the energy category. It may be noted that energy required for heating the building is not being included in the analysis as this is relevant only to a specific climatic region and does not relate to the particular type of technology chosen in the plant.

7.2 Economic Choices At The Sub-Process Level

The groups of operations identified in Chapter 6 and used as a basis for the disaggregation of dairy plant technology, can be used to facilitate the analysis of factor use and the subsequent derivation of economic relationships within the plant. These results serve to inform the discussion on "appropriate" technological choice with respect to a given economic environment.

The FORTRAN coded programme has been designed to compute economic values from the raw physical data which have emerged from the intensive engineering study of dairy processing. The basic physical factors used for this purpose, are intended to represent the alternative engineering designs available in such a way that most of the fundamental relationships would hold irrespective of the location in which the plant was made to function.

These "physical" factors have been quantified in the following way to simplify the analysis and to broaden the scope of application.

i) Physical plant - This is represented by the purchase price of the equipment and all the necessary accessories, along with the installation cost[1], expressed in U.K. (1980) prices[2]. Appropriate conversions to other years and currencies

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1 Accessories such as pumps, compressors, necessary conveyors and required piping is included in the price quoted. Most manufacturers install their own equipment and so quote an "installed" price which applies when the plant equipment is sold.

2 The use of U.K. prices for quantifying the physical capital does not restrict the wider applicability of the results. These prices reflect manufacturers' selling prices which must be expressed in a single currency to facilitate comparisons. All factor price variations are expressed in the same unit of currency.

can be made with use of engineering price indices and a suitable exchange rate.

ii) Floor space - This variable has been used to represent building space required so that building and construction costs for a particular area can be applied to compute the overhead plant cost.

iii) Electrical energy - The unit of electrical energy, the kilowatt hour (Kwh) is used to represent the energy consumption of the system as it is designed[1].

iv) Labour units - These units represent the equipment designers' concept of the number of persons required to give full or part-time attention to the process while it is running. For manual tasks, the units represent what may be described as high-efficiency labour. These figures can therefore be taken as the minimum labour requirement and upwards adjustments may be made with regard to the particular socio-economic context to which they are being applied.

v) Steam quantities - The steam requirements for a particular process are given in this form so that the value may be converted to boiler fuel requirements for any fuel which is cheap relative to others in any country[2].

vi) Water - The prevailing water rate in the country for which the analysis is being done can be applied. In some

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1 This includes requirements for thermal energy where this is provided by electricity, and for motor energy (for pumps, compressors, conveyors, etc.).

2 Relative cheapness of fuels is determined on the basis of the heat value per unit weight of the fuel in relation to the price per unit weight, and compared to other fuels.

countries the rates paid for water do not relate to the quantities used. Rates may be related instead to property values or location. For a private commercial enterprise, this variable would therefore not be relevant to the process. A social value may be attached where this is considered as appropriate.

Using the physical variables and applying the methods of evaluation discussed in Section 7.1 with varying factor price ratios, the nature of the economic functions can be examined for different environments, with respect to the major groups of operations described in Chapter 6 (Reception, Central processing, finishing and auxiliary).

The analysis is done with respect to scale effects, system substitutability and sensitivity to changes in relative factor prices. In obtaining factor prices to represent particular economic situations, there is a tendency to divide the countries of the world into the traditional binary classification of "developed" and "underdeveloped" (or "developing") countries with developed countries being characterised by "cheap" capital and "expensive" labour and vice versa for the underdeveloped countries. The real world situation is far more complex and, particularly because of the inclusion of variables representing primary and secondary sources of thermal and motor energy, the use of such a simplistic division would be practically meaningless. Even with the now more popular classifications which include labels such as "Industrial", "middle-income" and "oil-producing", the degree of homogeneity within groups can hardly justify the use of a representative set of factor prices on which policy prescriptions can be based for the group as a whole.

The study therefore does not purport to identify the factor price ratios that are or ought to be appreciable in any individual country or group of countries. The techniques used allow any set of factor prices to be applied and the results derived.

In order to demonstrate the applicability of the analytical techniques and to conduct the economic analysis some hypothetical economic extreme case situations are used. Only the three principle factors, designated as capital, labour and energy are varied to show the effect of relative prices on the economic (least cost) choices. For this initial analysis four sets of factor prices are used and referred to in the following way:

Economy 1 : $r = 0.14$; $\omega = 0.25$; $\varepsilon = 2.00$

Economy 2 : $r = 0.14$; $\omega = 0.25$; $\varepsilon = 0.25$

Economy 3 : $r = 0.07$; $\omega = 3.05$; $\varepsilon = 2.00$

Economy 4 : $r = 0.07$; $\omega = 3.05$; $\varepsilon = 0.25$

where

r is the rate of interest or opportunity cost for using capital funds in that activity;

ω is the hourly wage rate, and

ε is the energy tariff per Kilowatt hour.

These prices are used solely for illustrative purposes and the three factors represent only a part of the wider range of inputs for which prices can be set as parameters for the computing of total unit costs to evaluate the alternativesin different economic situations.

In this section the different relative prices are used to analyse the technological alternatives at the level of the individual sub-processes (group of food engineering operations) to illustrate the scope for technology choice and to emphasize the value of understanding the underlying real relationships instead of simply being given points on a cost curve, reflecting a single economic situation.

The analysis in this section is done to provide preliminary insights into the nature of the economic evaluation of the alternatives, which forms the basis for the less straightforward plant-level optimization procedure executed in the following section.

7.2.1 Economic relationships for reception technologies

Since it is being accepted in this thesis that the method by which the milk is transported to the dairy is determined by factors external to the plant[1], can and tanker reception systems are not considered as alternatives. As in Chapter 6, the alternatives for each of these systems are evaluated separately.

a) Can delivered milk

The major alternative technologies to be economically evaluated are categorized as:

i) Fully manual - manual tipping of cans, recording of weight/volume and fully manual washing of cans.

ii) Semi-manual - same as above except that cans are washed in a hand-turned rotary washer.

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1 This has already been mentioned in Chapter 1. Farm size refrigeration facilities, distance from plant etc. must be taken into account in the decision.

iii) Manually assisted - Mechanical aids are used to speed up the emptying of cans, and the cans are washed in a mechanical washer.

iv) Fully automatic - completely automatic can reception line with keypunch operation.

As with the other stages described in this section, the information on the relationship between inputs and outputs when prices are attached to the factors, is derived from the computation of the unit costs as the first part in the dynamic programming optimization procedure done for plant level optimization (see Appendix 7.1).

As various price ratios are attached to the "physical" factors of production used as the input to the optimization programme, the economic production and cost functions described, take on different characteristics and interpretations accordingly as the "underlying" production relations are obscured by the prices.

With prices attached to the factors, it now becomes possible however, to measure the relative costs of alternative systems to the final output. The importance of starting from first principles and defining the underlying production relations is done only to allow the "appropriate" relative factor prices to be attached so that the relationships described would have a more meaningful interpretation in the particular context.

For can-reception technologies, the physical factors have been described in relation to the four alternative systems (see above) each with a different composition of factor inputs. These four broad system technologies have each been further disaggregated by the capacity (speed or throughput rate) at which the system may be operated.

Thus in considering any given output (daily throughput volume), the quantity of factor inputs required depends not only on the system technology itself but also, in this case, on the throughput rate at which it is operated.

Once the factor prices have been fixed and the technical possibilities specified in terms of systems and capacities, the full range of alternative economic factor combinations can be computed and the least cost combination identified with respect to the particular set of factor prices used.

The most salient feature of the can reception technologies is that they all tend to be rather inflexible with respect to the variation in throughput speeds which are available on each system. As a result the problem of indivisibility arises both in relation to the throughput rates for which the alternative systems may be compared, and to the overall daily throughput volume of the dairy.

The two manual technologies (fully manual and semi-manual - (i and ii above) are especially inflexible in their ability to vary throughput rates. As a result an increase in throughput rate and an increase in the daily throughput volume to be handled by the system, requires system replication. This is generally the case where the speed of operation of a system is determined largely by the pace at which manual labour can be made to work.

The factor inputs therefore tend to increase pari-passu with discrete increases in throughput quantities and rates, which involve multiples of the capacity of the designed system. In between these points production requires another unit of fixed capital with variations in the units of the other factors used. The returns to scale are constant only at these discrete points.

The third can reception technology exhibits similar characteristics. Despite the use of a power conveyor (see Chapter 6) and a mechanical washer, the pace of the main activity (tipping of milk into weighbowl) is limited by physical manual capabilities. The system must be replicated for higher throughput rates and at discrete points for higher daily volumes. Because of the generally higher capacity of this system, however, the need for replication occurs less frequently with expanding output.

It is only with the fully automatic line that the pronounced indivisibilities in the relationship recedes. The possibilities for varying the capacity (throughput rate) of the system are greater. As the daily throughput volume is increased, smaller capacity systems may be replicated or larger ones selected. However, because of the way in which initial capital costs of equipment systems tend to increase less than proportionately with the capacity of the system, the larger capacity system becomes more cost effective where higher throughput rates are required to cope with higher daily throughput volumes. This is reinforced by the less-than-proportionate increase in the physical quantities of most of the other complementary factors of production as well, although in some cases (esp. electricity, water) this may not be as pronounced as in the case of initial costs. Nevertheless there is no offsetting increase in the physical factor requirements per unit of output capacity.

The returns to scale for the automatic technology are therefore of the increasing variety with

$$q = f(k, \ell, \varepsilon) = A \kappa^{\alpha} \ell^{\beta} \varepsilon^{\gamma}$$

where $\alpha + \beta + \gamma > 1$

where the factor ε includes energy and water requirements. κ and ℓ represent the usual capital and labour factors.

One feature of the highly mechanical and automated system designs is that the smallest capacity is usually some way above the smallest capacity for the manual or manually assisted systems. Where output at a throughput rate below that of the smallest capacity automatic or mechanical system is necessary or desirable, the indivisibility of the higher capacity system causes factor input quantities per unit output at these low levels, to be particularly high in comparison with the requirements at the higher levels.

In analysing the relationship between costs and outputs the use of data in tabular form is particularly attractive. The physical factor requirements for the different technologies and the different process capacities are input in tabular form so that the components may more easily be analysed for discrete levels of outputs. In this way it is possible to circumvent the problems caused by the irregular and varied nature of the relationships between physical inputs and outputs for the different alternatives. Because of the facility with which the D.P. technique, used for plant optimization, handles tabulated data, the analysis can be done at both the individual stage and the plant levels using the same input format.

An example of the way in which the economic relationships between inputs and outputs can be derived for a particular economic situation is given in Tables 7.1(a), (b) and (c), for can and for tank reception technologies. The daily throughput volume is varied for a constant factor price ratio. In this example the economic environment is characterized by a low wage with high capital and energy charges (Economy 1). The data illustrate the general structure of input factor components in output and the costs relevant to the particular economy.

For a small scale plant with a throughput of only 1,000 gallons of milk per day, the data indicate clearly that it would be uneconomical to use all but the smallest capacity of the fully manual technology. This is because of the need to replicate the system if a higher capacity (throughput rate) is desired. The same is true for the semi-manual system. For the technologies with higher capacity systems available (can systems 3 and 4), the lowest unit costs for this scale plant occur at throughput rates above the lowest level, because of the higher capacity design of the system. Overall, however, minimum cost operation at this scale would mean use of the smallest scale fully manual technology. The absence of electricity costs for system operation is a major contributing cause of this outcome.

In this economic environment characterised by low labour and high energy and interest charges, one striking feature of the data is that the minimum cost technology at larger

TABLE 7.1

Unit Costs for Reception Systems - Scale I

(£)

(Can Reception)

Q1: Q= 1,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN1	1000	53.58	0.00	1.52	1.51	0.04	56.65
CAN1	2000	107.13	0.00	1.52	1.51	0.04	110.20
CAN1	3000	111.39	0.00	1.27	1.51	0.04	114.21
CAN1	4000	164.94	0.00	1.33	1.51	0.04	167.82
CAN1	5000	218.64	0.00	1.37	1.51	0.04	221.56
CAN1	6000	222.74	0.00	1.27	1.51	0.04	225.56
CAN1	7000	276.29	0.00	1.31	1.51	0.04	279.14
CAN1	8000	330.14	0.00	1.33	1.51	0.04	333.03
CAN1	9000	334.40	0.00	1.27	1.51	0.04	337.22
CAN1	10000	373.26	0.00	1.29	1.51	0.04	376.11
CAN2	1000	56.39	1.80	1.02	4.23	0.10	63.54
CAN2	2000	112.78	1.80	1.02	4.23	0.10	119.94
CAN2	3000	115.66	1.20	0.69	2.82	0.07	120.43
CAN2	4000	172.05	1.35	0.77	3.18	0.07	177.42
CAN2	5000	228.44	1.44	0.82	3.39	0.08	234.16
CAN2	6000	231.31	1.20	0.69	2.82	0.07	236.09
CAN2	7000	287.70	1.29	0.73	3.02	0.07	292.82
CAN2	8000	344.09	1.35	0.77	3.18	0.07	349.46
CAN2	9000	346.97	1.20	0.69	2.82	0.07	351.75
CAN2	10000	388.98	1.26	0.72	2.96	0.07	393.99

Table 7.1. (cont'd)

UNIT RECEPTION COSTS

(Can Reception (cont'd))

Q1: Q=1,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN3	1000	77.17	39.60	0.63	4.84	0.13	122.38
CAN3	2000	77.17	19.80	0.32	2.42	0.07	99.78
CAN3	3000	79.17	13.87	0.22	2.02	0.05	95.33
CAN3	4000	82.29	10.40	0.17	1.66	0.04	94.55
CAN3	5000	107.83	13.64	0.16	2.18	0.06	123.86
CAN3	6000	109.83	11.70	0.13	2.02	0.05	123.73
CAN3	7000	116.05	10.03	0.12	1.99	0.04	128.23
CAN3	8000	123.88	10.10	0.12	2.12	0.05	136.27
CAN3	9000	127.61	9.20	0.11	2.02	0.05	138.98
CAN3	10000	150.55	11.00	0.15	2.00	0.05	163.74
CAN4	1000	88.70	39.60	0.63	4.84	0.13	133.91
CAN4	2000	88.70	19.80	0.32	2.42	0.07	111.31
CAN4	3000	90.70	13.87	0.22	2.02	0.05	106.86
CAN4	4000	101.21	12.55	0.17	1.66	0.07	115.66
CAN4	5000	113.21	13.64	0.11	2.18	0.06	129.19
CAN4	6000	115.21	11.70	0.09	2.02	0.05	129.07
CAN4	7000	121.43	10.03	0.08	1.99	0.04	133.58
CAN4	8000	129.26	10.10	0.09	2.12	0.05	141.62
CAN4	9000	131.26	9.20	0.08	2.02	0.05	142.61
CAN4	10000	134.41	9.54	0.07	2.00	0.05	146.07

Table 7.1. (cont'd)

UNIT RECEPTION COSTS

(Tanker Reception)

Q1: Q=1,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK1	1000	5.96	4.40	0.31	1.51	0.02	12.21
TNK1	2000	6.24	2.60	0.19	1.51	0.01	10.55
TNK1	3000	6.27	2.07	0.15	1.51	0.01	10.01
TNK1	4000	6.46	1.90	0.13	1.51	0.01	10.00
TNK1	5000	6.65	1.64	0.16	1.51	0.00	9.97
TNK1	6000	6.66	1.43	0.15	1.51	0.00	9.76
TNK1	7000	6.68	1.31	0.14	1.51	0.00	9.64
TNK1	8000	6.71	1.20	0.13	1.51	0.00	9.56
TNK1	9000	6.92	1.09	0.12	1.51	0.00	9.65
TNK1	10000	6.94	1.06	0.11	1.51	0.00	9.63
TNK2	1000	27.08	5.40	0.30	1.51	0.02	34.32
TNK2	2000	27.50	3.10	0.18	1.51	0.01	32.30
TNK2	3000	27.55	2.40	0.14	1.51	0.01	31.61
TNK2	4000	27.82	2.15	0.12	1.51	0.01	31.61
TNK2	5000	28.11	1.84	0.15	1.51	0.00	31.62
TNK2	6000	28.13	1.60	0.14	1.51	0.00	31.38
TNK2	7000	28.15	1.46	0.13	1.51	0.00	31.25
TNK2	8000	28.20	1.32	0.12	1.51	0.00	31.16
TNK2	9000	28.51	1.20	0.11	1.51	0.00	31.34
TNK2	10000	28.53	1.16	0.10	1.51	0.00	31.31

Table 7.1. (cont'd)

UNIT RECEPTION COSTS

(Tanker Reception (cont'd)) <u>Q1: Q=1,000 gal/day</u>

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK3	1000	11.62	4.60	0.30	1.51	0.02	18.06
TNK3	2000	11.91	2.70	0.18	1.51	0.01	16.31
TNK3	3000	12.14	2.13	0.14	1.51	0.01	15.93
TNK3	4000	12.45	1.95	0.12	1.51	0.01	16.04
TNK3	5000	12.58	1.64	0.15	1.51	0.00	15.89
TNK3	6000	12.66	1.47	0.14	1.51	0.00	15.78
TNK3	7000	12.87	1.34	0.13	1.51	0.00	15.86
TNK3	8000	13.11	1.20	0.12	1.51	0.00	15.94
TNK3	9000	13.26	1.11	0.11	1.51	0.00	15.99
TNK3	10000	13.27	1.08	0.10	1.51	0.00	15.97
TNK4	1000	29.62	4.80	0.56	1.51	0.02	36.52
TNK4	2000	29.90	2.70	0.31	1.51	0.01	34.44
TNK4	3000	29.93	2.20	0.23	1.51	0.01	33.88
TNK4	4000	30.11	2.05	0.19	1.51	0.01	33.87
TNK4	5000	30.31	1.76	0.21	1.51	0.00	33.80
TNK4	6000	30.32	1.57	0.19	1.51	0.00	33.60
TNK4	7000	30.34	1.43	0.17	1.51	0.00	33.45
TNK4	8000	30.37	1.30	0.16	1.51	0.00	33.35
TNK4	9000	30.58	1.20	0.15	1.51	0.00	33.45
TNK4	10000	30.60	1.12	0.14	1.51	0.00	33.37

Unit Costs for Reception Systems -Scale II

Table 7.1 (cont'd)

(£)

(Can Reception) Q2: Q=10,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN1	1000	10.72	0.00	1.50	1.51	0.04	13.77
CAN1	2000	10.71	0.00	1.50	1.51	0.04	13.76
CAN1	3000	11.14	0.00	1.25	1.51	0.04	13.94
CAN1	4000	16.49	0.00	1.31	1.51	0.04	19.36
CAN1	5000	21.86	0.00	1.35	1.51	0.04	24.77
CAN1	6000	22.27	0.00	1.25	1.51	0.04	25.08
CAN1	7000	27.63	0.00	1.29	1.51	0.04	30.47
CAN1	8000	33.01	0.00	1.31	1.51	0.04	35.88
CAN1	9000	33.44	0.00	1.25	1.51	0.04	36.24
CAN1	10000	37.33	0.00	1.28	1.51	0.04	40.15
CAN2	1000	11.28	1.80	1.00	4.23	0.10	18.42
CAN2	2000	11.28	1.80	1.00	4.23	0.10	18.41
CAN2	3000	11.57	1.20	0.67	2.82	0.07	16.32
CAN2	4000	17.20	1.35	0.75	3.18	0.07	22.56
CAN2	5000	22.84	1.44	0.80	3.39	0.08	28.55
CAN2	6000	23.13	1.20	0.67	2.82	0.07	27.89
CAN2	7000	28.77	1.29	0.72	3.02	0.07	33.87
CAN2	8000	34.41	1.35	0.75	3.18	0.07	39.76
CAN2	9000	34.70	1.20	0.67	2.82	0.07	39.46
CAN2	10000	38.90	1.26	0.70	2.96	0.07	43.89

Table 7.1 (cont'd)

UNIT RECEPTION COSTS

(Can Reception (cont'd))

Q2: Q=10,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN3	1000	15.43	39.60	0.63	4.84	0.13	60.64
CAN3	2000	7.72	19.80	0.31	2.42	0.07	30.32
CAN3	3000	7.92	13.87	0.21	2.02	0.05	24.06
CAN3	4000	8.23	10.40	0.16	1.66	0.04	20.49
CAN3	5000	10.78	13.64	0.15	2.18	0.06	26.81
CAN3	6000	10.98	11.70	0.13	2.02	0.05	24.88
CAN3	7000	11.61	10.03	0.11	1.99	0.04	23.77
CAN3	8000	12.39	10.10	0.11	2.12	0.05	24.77
CAN3	9000	12.76	9.20	0.10	2.02	0.05	24.13
CAN3	10000	15.06	11.00	0.14	2.00	0.05	28.24
CAN4	1000	17.74	39.60	0.63	4.84	0.13	62.94
CAN4	2000	8.87	19.80	0.31	2.42	0.07	31.47
CAN4	3000	9.07	13.87	0.21	2.02	0.05	25.21
CAN4	4000	10.12	12.55	0.16	1.66	0.07	24.56
CAN4	5000	11.32	13.64	0.10	2.18	0.06	27.30
CAN4	6000	11.52	11.70	0.08	2.02	0.05	25.37
CAN4	7000	12.14	10.03	0.07	1.99	0.04	24.28
CAN4	8000	12.93	10.10	0.08	2.12	0.05	25.28
CAN4	9000	13.13	9.20	0.07	2.02	0.05	24.46
CAN4	10000	13.44	9.54	0.06	2.00	0.05	25.09

Table 7.1 (cont'd)

UNIT RECEPTION COSTS
(Tanker Reception)

Q2: Q=10,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK1	1000	1.19	4.40	0.26	1.51	0.02	7.39
TNK1	2000	0.62	2.60	0.13	1.51	0.01	4.88
TNK1	3000	0.63	2.07	0.09	1.51	0.01	4.30
TNK1	4000	0.65	1.90	0.07	1.51	0.01	4.13
TNK1	5000	0.66	1.64	0.11	1.51	0.00	3.93
TNK1	6000	0.67	1.43	0.09	1.51	0.00	3.71
TNK1	7000	0.67	1.31	0.08	1.51	0.00	3.58
TNK1	8000	0.67	1.20	0.07	1.51	0.00	3.46
TNK1	9000	0.69	1.09	0.06	1.51	0.00	3.36
TNK1	10000	0.69	1.06	0.06	1.51	0.00	3.32
TNK2	1000	5.42	5.40	0.26	1.51	0.02	12.61
TNK2	2000	2.75	3.10	0.13	1.51	0.01	7.50
TNK2	3000	2.75	2.40	0.09	1.51	0.01	6.76
TNK2	4000	2.78	2.15	0.07	1.51	0.01	6.52
TNK2	5000	2.81	1.84	0.11	1.51	0.00	6.27
TNK2	6000	2.81	1.60	0.09	1.51	0.00	6.02
TNK2	7000	2.81	1.46	0.08	1.51	0.00	5.86
TNK2	8000	2.82	1.32	0.07	1.51	0.00	5.73
TNK2	9000	2.85	1.20	0.06	1.51	0.00	5.63
TNK2	10000	2.85	1.16	0.06	1.51	0.00	5.58

Table 7.1 (cont'd)

UNIT RECEPTION COSTS

(Tanker Reception (cont'd))

<u>Q2: Q=10,000 gal/day</u>

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK3	1000	2.32	4.60	0.26	1.51	0.02	8.72
TNK3	2000	1.19	2.70	0.13	1.51	0.01	5.54
TNK3	3000	1.21	2.13	0.09	1.51	0.01	4.96
TNK3	4000	1.25	1.95	0.07	1.51	0.01	4.78
TNK3	5000	1.26	1.64	0.11	1.51	0.00	4.52
TNK3	6000	1.27	1.47	0.09	1.51	0.00	4.34
TNK3	7000	1.29	1.34	0.08	1.51	0.00	4.22
TNK3	8000	1.31	1.20	0.07	1.51	0.00	4.09
TNK3	9000	1.33	1.11	0.06	1.51	0.00	4.01
TNK3	10000	1.33	1.08	0.06	1.51	0.00	3.98
TNK4	1000	5.92	4.80	0.51	1.51	0.02	12.77
TNK4	2000	2.99	2.70	0.26	1.51	0.01	7.47
TNK4	3000	2.99	2.20	0.17	1.51	0.01	6.89
TNK4	4000	3.01	2.05	0.13	1.51	0.01	6.71
TNK4	5000	3.03	1.76	0.16	1.51	0.00	6.46
TNK4	6000	3.03	1.57	0.13	1.51	0.00	6.25
TNK4	7000	3.03	1.43	0.11	1.51	0.00	6.09
TNK4	8000	3.04	1.30	0.10	1.51	0.00	5.95
TNK4	9000	3.06	1.20	0.09	1.51	0.00	5.86
TNK4	10000	3.06	1.12	0.08	1.51	0.00	5.78

Table 7.1 (cont'd)

Unit Costs for Reception Systems Scale III

(Can Reception) (£)   Q3: Q=30,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN1	1000	7.14	0.00	1.50	1.51	0.04	10.20
CAN1	2000	7.14	0.00	1.50	1.51	0.04	10.19
CAN1	3000	7.43	0.00	1.25	1.51	0.04	10.23
CAN1	4000	5.50	0.00	1.31	1.51	0.04	8.36
CAN1	5000	7.29	0.00	1.35	1.51	0.04	10.19
CAN1	6000	7.42	0.00	1.25	1.51	0.04	10.23
CAN1	7000	9.21	0.00	1.29	1.51	0.04	12.05
CAN1	8000	11.00	0.00	1.31	1.51	0.04	13.87
CAN1	9000	11.15	0.00	1.25	1.51	0.04	13.95
CAN1	10000	12.44	0.00	1.28	1.51	0.04	15.27
CAN2	1000	7.52	1.80	1.00	4.23	0.10	14.66
CAN2	2000	7.52	1.80	1.00	4.23	0.10	14.65
CAN2	3000	7.71	1.20	0.67	2.82	0.07	12.47
CAN2	4000	5.73	1.35	0.75	3.18	0.07	11.09
CAN2	5000	7.61	1.44	0.80	3.39	0.08	13.32
CAN2	6000	7.71	1.20	0.67	2.82	0.07	12.47
CAN2	7000	9.59	1.29	0.71	3.02	0.07	14.69
CAN2	8000	11.47	1.35	0.75	3.18	0.07	16.82
CAN2	9000	11.57	1.20	0.67	2.82	0.07	16.32
CAN2	10000	12.97	1.26	0.70	2.96	0.07	17.96

Table 7.1 (cont'd)

UNIT RECEPTION COSTS

(Can Reception (cont'd))

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN3	1000	10.29	39.60	0.63	4.84	0.13	55.49
CAN3	2000	5.14	19.80	0.31	2.42	0.07	27.74
CAN3	3000	5.28	13.87	0.21	2.02	0.05	21.42
CAN3	4000	2.74	10.40	0.16	1.66	0.04	15.00
CAN3	5000	3.59	13.64	0.15	2.18	0.06	19.62
CAN3	6000	3.66	11.70	0.13	2.02	0.05	17.55
CAN3	7000	3.87	10.03	0.11	1.99	0.04	16.04
CAN3	8000	4.13	10.10	0.11	2.12	0.05	16.51
CAN3	9000	4.25	9.20	0.10	2.02	0.05	15.62
CAN3	10000	5.02	11.00	0.14	2.00	0.05	18.20
CAN4	1000	11.83	39.60	0.63	4.84	0.13	57.03
CAN4	2000	5.91	19.80	0.31	2.42	0.07	28.51
CAN4	3000	6.05	13.87	0.21	2.02	0.05	22.19
CAN4	4000	3.37	12.55	0.16	1.66	0.07	17.81
CAN4	5000	3.77	13.64	0.10	2.18	0.06	19.75
CAN4	6000	3.84	11.70	0.08	2.02	0.05	17.69
CAN4	7000	4.05	10.03	0.07	1.99	0.04	16.18
CAN4	8000	4.31	10.10	0.08	2.12	0.05	16.66
CAN4	9000	4.38	9.20	0.07	2.02	0.05	15.71
CAN4	10000	4.48	9.54	0.06	2.00	0.05	16.13

UNIT RECEPTION COSTS

(Tanker Reception)

Table 7.1 (cont'd)

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK1	1000	0.79	4.40	0.26	1.51	0.02	6.99
TNK1	2000	0.42	2.60	0.13	1.51	0.01	4.67
TNK1	3000	0.42	2.07	0.09	1.51	0.01	4.09
TNK1	4000	0.22	1.90	0.06	1.51	0.01	3.70
TNK1	5000	0.22	1.64	0.10	1.51	0.00	3.48
TNK1	6000	0.22	1.43	0.09	1.51	0.00	3.26
TNK1	7000	0.22	1.31	0.07	1.51	0.00	3.13
TNK1	8000	0.22	1.20	0.06	1.51	0.00	3.00
TNK1	9000	0.23	1.09	0.06	1.51	0.00	2.89
TNK1	10000	0.23	1.06	0.05	1.51	0.00	2.86
TNK2	1000	3.61	5.40	0.26	1.51	0.02	10.80
TNK2	2000	1.83	3.10	0.13	1.51	0.01	6.59
TNK2	3000	1.84	2.40	0.09	1.51	0.01	5.84
TNK2	4000	0.93	2.15	0.06	1.51	0.01	4.66
TNK2	5000	0.94	1.84	0.10	1.51	0.00	4.40
TNK2	6000	0.94	1.60	0.09	1.51	0.00	4.14
TNK2	7000	0.94	1.46	0.07	1.51	0.00	3.98
TNK2	8000	0.94	1.32	0.06	1.51	0.00	3.84
TNK2	9000	0.95	1.20	0.06	1.51	0.00	3.72
TNK2	10000	0.95	1.16	0.05	1.51	0.00	3.68

Table 7.1 (cont'd)

UNIT RECEPTION COSTS

(Tanker Reception (cont'd))

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK3	1000	1,55	4.60	0.26	1.51	0.02	7.94
TNK3	2000	0.79	2.70	0.13	1.51	0.01	5.15
TNK3	3000	0.81	2.13	0.09	1.51	0.01	4.55
TNK3	4000	0.42	1.95	0.06	1.51	0.01	3.95
TNK3	5000	0.42	1.64	0.10	1.51	0.00	3.68
TNK3	6000	0.42	1.47	0.09	1.51	0.00	3.49
TNK3	7000	0.43	1.34	0.07	1.51	0.00	3.36
TNK3	8000	0.44	1.20	0.06	1.51	0.00	3.22
TNK3	9000	0.44	1.11	0.06	1.51	0.00	3.13
TNK3	10000	0.44	1.08	0.05	1.51	0.00	3.09
TNK4	1000	3.95	4.80	0.51	1.51	0.02	10.79
TNK4	2000	1.99	2.70	0.25	1.51	0.01	6.47
TNK4	3000	2.00	2.20	0.17	1.51	0.01	5.89
TNK4	4000	1.00	2.05	0.13	1.51	0.01	4.70
TNK4	5000	1.01	1.76	0.15	1.51	0.00	4.44
TNK4	6000	1.01	1.57	0.13	1.51	0.00	4.22
TNK4	7000	1.01	1.43	0.11	1.51	0.00	4.06
TNK4	8000	1.01	1.30	0.10	1.51	0.00	3.92
TNK4	9000	1.02	1.20	0.09	1.51	0.00	3.82
TNK4	10000	1.02	1.12	0.08	1.51	0.00	3.73

scales of production remains the fully manual system, despite the need to replicate the system. Understandably, the difference between the unit costs of this system and the automated system narrows particularly at high capacity levels, and the unit capital costs of the automated and more mechanized system eventually falls below that of the manual system but only at very large scales. The major cost advantage held by the manual system in this hypothetical economy derives from the little considered variable in empirical economic analyses of production - energy (thermal and motor).

Using the basic physical data derived from the engineering design variables the differences in the least cost choices in another hypothetical economy with different factor price ratios, are similarly deduced. Further results indicate that in Economy 2 where capital and labour charges are the same as in the example above but with very cheap energy ($\frac{1}{8}$ that in previous situation), by the time a modest scale of 10,000 gallons per day is reached, the manual technology has lost its competitiveness and the mechanical and automatic technologies (iii and iv) show lower total unit costs.

With the relatively high wages in Economy 3, the manual technology again soon loses its competitiveness to the more mechanical and to the automatic by the time the modest scale of 10,000 gallons per day is reached.

Clearly then in addition to knowing the lowest cost for producing a given output, it is important to be able to identify the particular technology responsible for this low cost and to find the optimal capacity at which the system gives the lowest cost. The points in the cost function drawn for can reception would represent different alternatives at different output levels, for any given set of factor prices.

b) Tanker delivered milk

With tanker reception systems the situation is somewhat different. There is no fully manual system as in the can reception systems. The labour hours required vary only slightly among the four alternative systems and, along with electricity costs, depend mainly on the capacity at which the process is operated (i.e. the total elapsed time of the process).

The four tanker systems being evaluated here are

i) The In-line metering system, with manual control (push-button).

ii) The In-line metering system with microprocessor control of the intake.

iii) The load cell system, and

iv) The weighbridge system.

The physical characteristics of these alternative systems have been described in Chapter 6. The possibilities for factor substitution are much more limited in this case than they are for can reception systems. The major difference lies in the initial capital requirements of the alternative systems in relation to the capacity of the system. Table 7.1 ((a) and (b), (c)) show the differences in unit costs for three levels of output, holding factor prices constant.

Because of the design of the tanker reception systems to accommodate larger throughput capacities, one feature of these technologies is the reduction in unit costs as the capacity of the system is increased and as the daily throughput volume increases. The tabulated data indicate that the in-line metering system with manual control has the lowest unit cost for the scale of plants considered. This is so even up to a daily throughput volume of 50,000 gallons. However as scale is increased, the difference in the unit costs among the systems diminishes and there is much greater freedom to choose. By the time a scale of 30,000 gallons per day is reached, the more expensive microprocessor intake system has become a realistic though not lower cost alternative in Economy 1 even with its relatively high capital and energy charges.

Because of the slight use of labour by these four systems and the similarity in the quantity of energy required, the relative positions of the technologies are virtually unaltered by changes in relative factor prices.

7.2.2 Economic relationships for pasteurization technologies

The two major technological alternatives at the pasteurization stage (Batch and H.T.S.T.) are very dissimilar in their response to scale effects and in the factor composition in output. The batch technology, like the manual can reception systems has fairly narrow restrictions on the process capacity (vat size and holding time for pasteurization), and so replication of system is necessary at discrete points as the system capacity is expanded. This therefore limits the extent to which capital costs per unit of output decline with expansion in daily processing volume. At these discrete points the returns to scale are constant.

On the contrary, the continuous H.T.S.T. system has a much wider capacity range where increasingly higher process capacities can be obtained with initial costs increasing less than proportionately with output. This, together with the tendency for unit costs for labour, electricity and fuel to diminish slightly with increasing system capacity or, in the limit, to remain constant, allows for increasing returns to scale for the continuous H.T.S.T. technology.

The systems are also very different in their use of the operating factors (electricity, fuel, labour) and so their relative costs are very much affected by the relative factor prices prevailing in the different economic situations. The H.T.S.T. system, because of its regenerative design and the high heat transfer co-efficient[1] of the plate heat exchanger, is very low in thermal energy consumption, in comparison with the vat (batch) system. The H.T.S.T. system also requires less supervision and by operating at higher capacities, fewer labour hours are required for a given daily throughput volume than with the batch process. Table 7.2 ((a), (b), (c)) show the comparative unit costs for the two alternatives in relation to process capacities for three different daily throughput volumes holding factor prices constant (Economy 1).

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1 Discussed in Chapter 3.

TABLE 7.2

Unit Costs for Pasteurization Systems - Scale I

(Batch and H.T.S.T.) (£) Q1: Q=1,000 Gal/day

TECHNOLOGY	CAPITAL	LABOUR	ELECTRICITY	FUEL	TOTAL PAST. COSTS
BTH1	30.70	12.60	166.32	11.61	221.22
BTH2	15.39	6.80	89.76	12.36	124.31
BTH3	8.28	3.90	51.48	14.18	77.84
BTH4	8.93	2.45	32.34	17.82	61.53
BTH5	10.14	1.97	25.96	21.45	59.52
HTT1	30.84	2.50	88.00	0.44	121.78
HTT2	21.19	1.25	44.00	0.63	67.07
HTT3	17.29	0.62	45.00	0.78	63.69
HTT4	18.36	0.25	18.00	2.04	38.64
HTT5	19.17	0.16	11.25	2.55	33.12
HTT6	28.48	0.12	25.00	4.07	57.68
HTT7	44.86	0.06	15.20	8.06	68.18
HTT8	46.25	0.04	10.13	12.22	68.64
HTT9	49.58	0.02	7.36	20.34	77.30
HT10	55.69	0.02	5.15	32.53	93.38

Table 7.2 (cont'd)

Unit Costs for Pasteruization Systems - Scale II

(Batch and H.T.S.T.)(£) Q2: Q=10,000 gal/day

TECHNOLOGY	CAPITAL	LABOUR	ELECTRICITY	FUEL	TOTAL PAST. COSTS
BTH1	24.56	12.60	166.32	11.61	215.08
BTH2	13.08	6.80	89.76	12.36	122.01
BTH3	8.28	3.90	51.48	14.18	77.84
BTH4	6.25	2.45	32.34	17.82	58.85
BTH5	5.07	1.97	25.96	21.45	54.45
HTT1	26.73	2.50	88.00	0.32	117.55
HTT2	13.78	1.25	44.00	0.33	59.35
HTT3	12.10	0.62	45.00	0.37	58.09
HTT4	5.51	0.25	18.00	0.46	24.22
HTT5	3.83	0.16	11.25	0.39	15.63
HTT6	5.70	0.12	25.00	0.67	31.49
HTT7	4.49	0.06	15.20	0.81	20.55
HTT8	4.62	0.04	10.13	1.22	16.02
HTT9	4.96	0.02	7.36	2.03	14.38
HT10	5.57	0.02	5.15	3.25	13.99

Table 7.2 (cont'd)

Unit Costs for Pasteurization Systems - Scale III

(Batch and H.T.S.T.)(£) Q3: Q=30,000 gal/hr

TECHNOLOGY	CAPITAL	LABOUR	ELECTRICITY	FUEL	TOTAL PAST. COSTS
BTH1	24.30	12.60	166.32	11.61	214.83
BTH2	13.08	6.80	89.76	12.36	122.01
BTH3	8.28	3.90	51.48	14.18	77.84
BTH4	5.65	2.45	32.34	17.82	58.26
BTH5	5.07	1.97	25.96	21.45	54.45
HTT1	26.05	2.50	88.00	0.31	116.86
HTT2	13.42	1.25	44.00	0.31	58.98
HTT3	10.95	0.62	45.00	0.32	56.89
HTT4	4.89	0.25	18.00	0.37	23.52
HTT5	3.20	0.16	11.25	0.27	14.87
HTT6	3.80	0.12	25.00	0.40	29.32
HTT7	2.99	0.06	15.20	0.44	18.69
HTT8	3.08	0.04	10.13	0.67	13.92
HTT9	1.65	0.02	7.36	0.68	9.72
HT10	1.86	0.02	5.15	1.08	8.11

In the hypothetical Economy 1, with relatively high capital and energy charges and low labour rates, the continuous (H.T.S.T.) technology (operated at capacity level 5 - 800 gals/hr) comes out with the least cost value for the small scale plant producing with a daily throughput volume of 1,000 gallons. The cost advantages of the H.T.S.T. system become more pronounced as the scale of the plant increases.

In Economy 2 characterized by the same capital and labour charge but with a much lower energy tariff, the H.T.S.T. system retains its superior cost effectiveness. This advantageous position of the H.T.S.T. system remains through all the economic conditions simulated, and even for the smallest input quantity considered (1,000 gals.). The best prospects for use of the vat system however are found at the lower end of the scale.

7.2.3 Economic relationships for filling technologies

The range of filling alternatives is the widest in the groups of operations being considered as sub-processes in this thesis. The choice is at three levels, i) choice of container technology, ii) choice of capacity at which that technology should be operated, and iii) choice of the extent of manual involvement (see Chapter 6).

The three broad container groups use the factors of production in widely varying real quantities and so the changes in relative factor prices have a significant effect on the relative total unit costs of the various container systems. As discussed in Chapter 6, the different container systems involve different activities (for glass bottles, bottle washing operations must be included, for plastic bottles their manufacturing operation must be included) which must all be evaluated for a final comparison. Table 7.3 ((a), (b), (c)) provides details of these costs for the factor prices prevailing in the hypothetical Economy 1.

All the technologies display the same pattern for the small scale output (1,000 gallons per day) with increasing unit capital costs with increasing system capacity, with a reducing trend in the unit costs of the variable factors.

For a throughput of 1,000 gallons per day, the table shows the favourable comparative cost position of the manual glass bottle filling technique, for the economic situation characterized by a relatively high capital and energy charges and low labour charges. The manual glass bottling system is optimal in this Economy when operated at its smallest capacity (225 gals./hr or 30 bottles/min.). This technology involves a fairly sizeable number of labour units for manual washing of cases, and, although manual washing of bottles is not considered, there is manual handling of the bottles entering and leaving the "come-back" type of mechanical washer. The standard automatic filler

TABLE 7.3

Unit Costs for Filling Systems - Scale 1

(Glass Bottle Filling) (£) Q1: Q=1,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
BOTM	225	41.09	24.89	4.56	7.44	0.74	0.55	79.27
BOTM	450	51.95	20.00	2.83	7.44	0.50	0.55	83.27
BOTM	600	65.96	18.00	2.96	7.31	0.40	0.55	95.17
BOTM	900	77.05	16.22	2.81	7.51	0.38	0.55	104.52
BOTM	1200	92.18	15.67	2.52	6.30	0.38	0.55	117.59
BOTM	1500	115.24	17.47	2.50	7.36	0.42	0.55	143.52
BOTM	2200	148.49	16.73	2.39	6.21	0.39	0.55	174.75
BOTM	3000	197.40	14.53	2.25	6.08	0.38	0.55	221.19
BOTM	3700	277.98	14.05	2.30	5.95	0.37	0.55	301.21
BOTM	4500	328.85	13.47	2.22	5.79	0.36	0.55	351.24
BOMA	225	44.66	72.89	2.22	13.30	1.07	0.55	134.69
BOMA	450	53.75	40.89	1.11	9.74	0.63	0.55	106.66
BOMA	600	65.99	37.33	1.25	8.72	0.47	0.55	114.31
BOMA	900	75.32	31.56	1.39	8.03	0.40	0.55	117.25
BOMA	1200	87.70	33.33	1.04	6.95	0.47	0.55	130.05
BOMA	1500	107.23	30.00	1.00	7.63	0.47	0.55	146.88
BOMA	2200	134.20	25.91	0.91	5.99	0.41	0.55	167.97
BOMA	3000	178.87	28.00	0.83	6.51	0.41	0.55	215.17
BOMA	3700	253.51	26.49	0.88	6.06	0.37	0.55	287.86
BOMA	4500	297.61	24.89	0.83	5.93	0.37	0.55	330.18
BOTA	225	70.39	92.44	1.39	19.48	1.26	0.55	185.51
BOTA	450	71.61	46.22	0.69	9.74	0.63	0.55	129.44
BOTA	600	99.47	54.00	0.52	11.74	0.55	0.55	166.83
BOTA	900	119.56	42.89	0.35	8.50	0.48	0.55	172.32
BOTA	1200	144.50	51.67	0.26	7.38	0.58	0.55	204.94
BOTA	1500	144.50	41.33	0.21	5.90	0.46	0.55	192.96
BOTA	2200	166.49	35.09	0.14	4.76	0.35	0.55	207.39
BOTA	3000	181.25	30.73	0.10	4.65	0.34	0.55	217.63
BOTA	3700	225.83	32.00	0.08	4.40	0.33	0.55	263.19
BOTA	4500	255.16	29.87	0.07	3.96	0.30	0.55	289.92

Table 7.3 (cont'd)

UNIT FILLING COSTS

(Plastic Bottles & Cartons) Q1: Q=1,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
PLBT	225	81.30	320.00	3.33	0.00	4.22	8.75	417.61
PLBT	450	121.31	226.67	1.67	0.00	3.89	8.75	362.28
PLBT	600	170.98	230.00	2.08	0.00	3.75	8.75	415.56
PLBT	900	217.72	188.89	1.67	0.00	3.33	8.75	420.36
PLBT	1200	242.77	166.67	1.25	0.00	3.12	8.75	422.56
PLBT	1500	277.73	166.67	1.17	0.00	2.83	8.75	457.15
PLBT	2200	318.38	168.18	0.91	0.00	2.27	8.75	498.50
PLBT	3000	374.42	152.00	0.75	0.00	2.10	8.75	538.02
PLBT	3700	409.21	156.22	0.68	0.00	1.82	8.75	576.68
PLBT	4500	420.94	155.56	0.61	0.00	1.58	8.75	587.43
CARM	225	27.80	88.00	1.11	0.05	0.12	13.95	131.03
CARM	450	37.50	52.00	1.11	0.11	0.09	13.95	104.76
CARM	600	56.16	44.33	0.83	0.18	0.07	13.95	115.53
CARM	900	66.82	50.00	0.83	0.22	0.07	13.95	131.90
CARM	1200	115.31	50.83	0.62	0.18	0.07	13.95	180.97
CARM	1500	133.64	74.13	1.00	0.24	0.06	13.95	223.03
CARM	2200	196.15	71.27	1.02	0.20	0.06	13.95	282.65
CARM	3000	258.30	63.47	1.00	0.24	0.06	13.95	337.01
CARM	3700	319.51	56.22	1.01	0.22	0.06	13.95	390.96
CARM	4500	363.88	60.00	1.00	0.20	0.06	13.95	439.08
CARA	225	54.00	105.78	1.11	0.05	0.09	13.95	174.97
CARA	450	70.44	60.89	0.56	0.11	0.09	13.95	146.04
CARA	600	113.82	57.67	0.42	0.18	0.07	13.95	186.10
CARA	900	146.13	57.33	0.28	0.18	0.07	13.95	217.94
CARA	1200	168.51	52.50	0.21	0.17	0.07	13.95	235.41
CARA	1500	189.85	52.00	0.17	0.17	0.07	13.95	256.21
CARA	2200	236.18	40.00	0.11	0.16	0.07	13.95	290.46
CARA	3000	275.69	32.67	0.08	0.13	0.06	13.95	322.59
CARA	3700	311.05	30.27	0.07	0.12	0.06	13.95	355.52
CARA	4500	341.74	28.89	0.06	0.11	0.05	13.95	384.79

Table 7.3 (cont'd)

Unit Costs for Filling Systems - Scale II

(Glass Bottle Filling) (£) Q2: Q=10,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
BOTM	225	24.66	24.89	4.56	7.44	0.74	0.55	62.83
BOTM	450	15.58	20.00	2.83	7.44	0.50	0.55	46.91
BOTM	600	19.79	18.00	2.96	7.31	0.40	0.55	49.00
BOTM	900	15.41	16.22	2.81	7.51	0.38	0.55	42.87
BOTM	1200	18.44	15.67	2.52	6.30	0.38	0.55	43.85
BOTM	1500	11.52	17.47	2.50	7.36	0.42	0.55	39.81
BOTM	2200	14.85	16.73	2.39	6.21	0.39	0.55	41.11
BOTM	3000	19.74	14.53	2.25	6.08	0.38	0.55	43.53
BOTM	3700	27.80	14.05	2.30	5.95	0.37	0.55	51.02
BOTM	4500	32.89	13.47	2.22	5.79	0.36	0.55	55.27
BOMA	225	26.80	72.89	2.22	13.30	1.07	0.55	116.82
BOMA	450	16.12	40.89	1.11	9.74	0.63	0.55	69.04
BOMA	600	19.80	37.33	1.25	8.72	0.47	0.55	68.12
BOMA	900	15.06	31.56	1.39	8.03	0.40	0.55	56.99
BOMA	1200	17.54	33.33	1.04	6.95	0.47	0.55	59.89
BOMA	1500	10.72	30.00	1.00	7.63	0.47	0.55	50.37
BOMA	2200	13.42	25.91	0.91	5.99	0.41	0.55	47.19
BOMA	3000	17.89	28.00	0.83	6.51	0.41	0.55	54.19
BOMA	3700	25.35	26.49	0.88	6.06	0.37	0.55	59.70
BOMA	4500	29.76	24.89	0.83	5.93	0.37	0.55	62.33
BOTA	225	42.23	92.44	1.39	19.48	1.26	0.55	157.35
BOTA	450	21.48	46.22	0.69	9.74	0.63	0.55	79.32
BOTA	600	29.84	54.00	0.52	11.74	0.55	0.55	97.21
BOTA	900	23.91	42.89	0.35	8.50	0.48	0.55	76.67
BOTA	1200	28.90	51.67	0.26	7.38	0.58	0.55	89.33
BOTA	1500	14.45	41.33	0.21	5.90	0.46	0.55	62.91
BOTA	2200	16.65	35.09	0.14	4.76	0.35	0.55	57.54
BOTA	3000	18.13	30.73	0.10	4.65	0.34	0.55	54.50
BOTA	3700	22.58	32.00	0.08	4.40	0.33	0.55	59.95
BOTA	4500	25.52	29.87	0.07	3.96	0.30	0.55	60.27

Table 7.3 (cont'd)

UNIT FILLING COSTS
(Plastic Bottles & Cartons)　Q2: Q=10,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
PLBT	225	48.78	320.00	3.33	0.00	4.22	8.75	385.09
PLBT	450	36.39	226.67	1.67	0.00	3.89	8.75	277.36
PLBT	600	51.29	230.00	2.08	0.00	3.75	8.75	295.88
PLBT	900	43.54	188.89	1.67	0.00	3.33	8.75	246.18
PLBT	1200	48.55	166.67	1.25	0.00	3.12	8.75	228.35
PLBT	1500	27.77	166.67	1.17	0.00	2.83	8.75	207.19
PLBT	2200	31.84	168.18	0.91	0.00	2.27	8.75	211.95
PLBT	3000	37.44	152.00	0.75	0.00	2.10	8.75	201.04
PLBT	3700	40.92	156.22	0.68	0.00	1.82	8.75	208.39
PLBT	4500	42.09	155.56	0.61	0.00	1.58	8.75	208.59
CARM	225	16.68	88.00	1.11	0.05	0.12	13.95	119.91
CARM	450	11.25	52.00	1.11	0.11	0.09	13.95	78.51
CARM	600	16.85	44.33	0.83	0.18	0.07	13.95	76.21
CARM	900	13.36	50.00	0.83	0.22	0.07	13.95	78.44
CARM	1200	23.06	50.83	0.62	0.18	0.07	13.95	88.72
CARM	1500	13.36	74.13	1.00	0.24	0.06	13.95	102.75
CARM	2200	19.62	71.27	1.02	0.20	0.06	13.95	106.11
CARM	3000	25.83	63.47	1.00	0.24	0.06	13.95	104.54
CARM	3700	31.95	56.22	1.01	0.22	0.06	13.95	103.40
CARM	4500	36.39	60.00	1.00	0.20	0.06	13.95	111.59
CARA	225	32.40	105.78	1.11	0.05	0.09	13.95	153.37
CARA	450	21.13	60.89	0.56	0.11	0.09	13.95	96.73
CARA	600	34.14	57.67	0.42	0.18	0.07	13.95	106.43
CARA	900	29.23	57.33	0.28	0.18	0.07	13.95	101.04
CARA	1200	33.70	52.50	0.21	0.17	0.07	13.95	100.60
CARA	1500	18.99	52.00	0.17	0.17	0.07	13.95	85.34
CARA	2200	23.62	40.00	0.11	0.16	0.07	13.95	77.91
CARA	3000	27.57	32.67	0.08	0.13	0.06	13.95	74.46
CARA	3700	31.10	30.27	0.07	0.12	0.06	13.95	75.57
CARA	4500	34.17	28.89	0.06	0.11	0.05	13.95	77.23

Table 7.3 (cont'd)

Unit Costs for Filling Systems - Scale III

(Glass Bottle Filling)(£) Q3: Q=30,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
BOTM	225	23.29	24.89	4.56	7.44	0.74	0.55	61.46
BOTM	450	15.58	20.00	2.83	7.44	0.50	0.55	46.91
BOTM	600	15.39	18.00	2.96	7.31	0.40	0.55	44.60
BOTM	900	12.84	16.22	2.81	7.51	0.38	0.55	40.31
BOTM	1200	12.29	15.67	2.52	6.30	0.38	0.55	37.70
BOTM	1500	11.52	17.47	2.50	7.36	0.42	0.55	39.81
BOTM	2200	9.90	16.73	2.39	6.21	0.39	0.55	36.16
BOTM	3000	13.16	14.53	2.25	6.08	0.38	0.55	36.95
BOTM	3700	18.53	14.05	2.30	5.95	0.37	0.55	41.76
BOTM	4500	10.96	13.47	2.22	5.79	0.36	0.55	33.35
BOMA	225	25.31	72.89	2.22	13.30	1.07	0.55	115.33
BOMA	450	16.12	40.89	1.11	9.74	0.63	0.55	69.04
BOMA	600	15.40	37.33	1.25	8.72	0.47	0.55	63.72
BOMA	900	12.55	31.56	1.39	8.03	0.40	0.55	54.48
BOMA	1200	11.69	33.33	1.04	6.95	0.47	0.55	54.04
BOMA	1500	10.72	30.00	1.00	7.63	0.47	0.55	50.37
BOMA	2200	8.95	25.91	0.91	5.99	0.41	0.55	42.72
BOMA	3000	11.92	28.00	0.83	6.51	0.41	0.55	48.22
BOMA	3700	16.90	26.49	0.88	6.06	0.37	0.55	51.25
BOMA	4500	9.92	24.89	0.83	5.93	0.37	0.55	42.49
BOTA	225	39.89	92.44	1.39	19.48	1.26	0.55	155.01
BOTA	450	21.48	46.22	0.69	9.74	0.63	0.55	79.32
BOTA	600	23.21	54.00	0.52	11.74	0.55	0.55	90.58
BOTA	900	19.93	42.89	0.35	8.50	0.48	0.55	72.69
BOTA	1200	19.27	51.67	0.26	7.38	0.58	0.55	79.70
BOTA	1500	14.45	41.33	0.21	5.90	0.46	0.55	62.91
BOTA	2200	11.10	35.09	0.14	4.76	0.35	0.55	51.99
BOTA	3000	12.08	30.73	0.10	4.65	0.34	0.55	48.46
BOTA	3700	15.06	32.00	0.08	4.40	0.33	0.55	52.42
BOTA	4500	8.51	29.87	0.07	3.96	0.30	0.55	43.26

Table 7.3 (cont'd)

UNIT FILLING COSTS
(Plastic Bottles and Cartons)

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
PLBT	225	46.07	320.00	3.33	0.00	4.22	8.75	382.38
PLBT	450	36.39	226.67	1.67	0.00	3.89	8.75	277.36
PLBT	600	39.90	230.00	2.08	0.00	3.75	8.75	284.48
PLBT	900	36.29	188.89	1.67	0.00	3.33	8.75	238.93
PLBT	1200	32.37	166.67	1.25	0.00	3.12	8.75	212.16
PLBT	1500	27.77	166.67	1.17	0.00	2.83	8.75	207.19
PLBT	2200	21.23	168.18	0.91	0.00	2.27	8.75	201.34
PLBT	3000	24.96	152.00	0.75	0.00	2.10	8.75	188.56
PLBT	3700	27.28	156.22	0.68	0.00	1.82	8.75	194.75
PLBT	4500	14.03	155.56	0.61	0.00	1.58	8.75	180.53
CARM	225	15.76	88.00	1.11	0.05	0.12	13.95	118.99
CARM	450	11.25	52.00	1.11	0.11	0.09	13.95	78.51
CARM	600	13.10	44.33	0.83	0.18	0.07	13.95	72.47
CARM	900	11.14	50.00	0.83	0.22	0.07	13.95	76.21
CARM	1200	15.37	50.83	0.62	0.18	0.07	13.95	81.03
CARM	1500	13.36	74.13	1.00	0.24	0.06	13.95	102.75
CARM	2200	13.08	71.27	1.02	0.20	0.06	13.95	99.58
CARM	3000	17.22	63.47	1.00	0.24	0.06	13.95	95.93
CARM	3700	21.30	56.22	1.01	0.22	0.06	13.95	92.75
CARM	4500	12.13	60.00	1.00	0.20	0.06	13.95	87.34
CARA	225	30.60	105.78	1.11	0.05	0.09	13.95	151.57
CARA	450	21.13	60.89	0.56	0.11	0.09	13.95	96.73
CARA	600	26.56	57.67	0.42	0.18	0.07	13.95	98.84
CARA	900	24.35	57.33	0.28	0.18	0.07	13.95	96.16
CARA	1200	22.47	52.50	0.21	0.17	0.07	13.95	89.37
CARA	1500	18.99	52.00	0.17	0.17	0.07	13.95	85.34
CARA	2200	15.75	40.00	0.11	0.16	0.07	13.95	70.03
CARA	3000	18.38	32.67	0.08	0.13	0.06	13.95	65.27
CARA	3700	20.74	30.27	0.07	0.12	0.06	13.95	65.20
CARA	4500	11.39	28.89	0.06	0.11	0.05	13.95	54.45

is used with all technologies.

The position of bottling technology as a whole is enhanced by the recycling of bottles. The costs of cartons and of bottles are usually quite similar in magnitude, however, with the returnable bottle (as opposed to the disposable carton) the relative costs of the bottles are reduced to an extent depending on the life (i.e. number of trips) of the bottle. The benefits of bottle reuse are partially offset by the washing requirements for the returned "empties". It is therefore important that container costs should be included for a proper economic evaluation of the alternative container technologies, and this is done for this analysis.

For Economy 1 the superiority of the manual glass bottle filling over all other container types and other bottle filling technoligies is established. The term "manual", in this case, is a bit of a misnomer, however, since the actual filling is done with the standard automatic filler. It is in only the peripheral operations (washing of cases, handling of bottles) that extra labour units are required. With low labour costs the extra labour does not impose any substantial burden on total unit costs, and these extra costs are more than offset by the reduction in energy consumption through the manual washing of cases, assistance at bottle washing equipment and manual casing of bottles.

The cost advantage of the "manual" bottling system is maintained throughout the range of daily throughput volumes considered. Plastic bottling technology comes out particularly unfavourably because of the high capital requirement for the bottle manufacturing equipment and the high energy consumption of the plastic bottle manufacturing process. The carton fillers have slightly higher energy requirements than the "manual" bottling system as the cartons are heat sealed. Thus when the choices are examined within the context of Economy 2 with lower energy prices, the "manual" carton technology (manual casing of cartons) assumes the more favourable cost position. This is returned to the bottling technologies as output expands because of the effect of the more steeply falling unit capital costs with higher system capacities, takes precedence over other effects.

As expected, the automatic technologies improve their standing as the relative positions of labour and capital costs are reversed as in hypothetical Economy 3. It is still within the glass bottle technological systems that the lowest unit costs are to be found.

7.2.4 Economic Relationships for Stacking Technologies

In Chapter 6, two alternative stacking and loading technologies were described. The manual handling method using a two-wheel case trolley and what may be described as the auto-mechanical method with automatic stacking equipment along with a fork lift truck for stacking and loading.

Because of the extremely low capital requirement for the manual stacking operation and the virtual absence of motor or thermal energy costs the system is characterised by relatively low unit costs even at the highest output levels considered for Economy 1 (50,000 gal./day, despite the need for replication at very short intervals. Account is taken of the alterations that would have to be made to existing equipment to allow the two types of stacking alternatives to be technically feasible. For example, where a high speed filling and casing line is to be stacked manually the case output lines would need to be branched to facilitate the pick up of cases by some multiple of more slowly operating manual stackers, and vice versa where cases are moved from several slower manual casing lines to higher speed auto-mechanical stacking equipment.

When all this is taken into account the manual stacking technology is found to hold its supremacy in the cost league up to large scales particularly when the input is coming from the already branched lines of a manual casing operation. At very large scales, however, even in the relatively low-wage Economy 1, the unit costs of the automatic stacking system, when coming from an automatic line are lower at some daily throughput volumes than for manual stacking from automatic lines. (See Table 7.4).

Where the economic situation is characterized by high labour-capital ratios as in Economy 4, the automatic stacking and loading systems begin to show lower total unit costs from the middle ranges of the scale spectrum (10,000 gals./day).

The choices which would give the lowest total unit cost at any desired output level in a given economic situation can

TABLE 7.4

Unit Costs for Stacking Systems - Scale I

(£)

(Automatic Stacking)

Q1: Q=1,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAA	225	21.37	22.22	1.39	44.98
SKAA	450	21.37	11.11	0.69	33.18
SKAA	600	21.37	10.00	0.52	31.89
SKAA	900	21.37	6.67	0.35	28.38
SKAA	1200	21.37	5.83	0.26	27.46
SKAA	1500	23.53	4.67	0.21	28.40
SKAA	2200	25.04	3.64	0.14	28.81
SKAA	3000	26.85	2.67	0.10	29.62
SKAA	3700	27.66	2.43	0.08	30.18
SKAA	4500	28.12	2.22	0.07	30.41
SKMA	225	23.40	26.67	1.39	51.46
SKMA	450	23.40	13.33	0.69	37.43
SKMA	600	23.40	11.67	0.52	35.59
SKMA	900	23.40	7.78	0.35	31.53
SKMA	1200	23.40	7.50	0.26	31.16
SKMA	1500	25.43	6.67	0.21	32.31
SKMA	2200	26.87	5.45	0.14	32.47
SKMA	3000	32.90	4.00	0.10	37.01
SKMA	3700	33.49	3.78	0.08	37.36
SKMA	4500	36.84	3.56	0.07	40.46

Table 7.4 (cont'd)

UNIT STACKING COSTS

(Manual Stacking Systems)

Q1: Q=1,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAM	225	Ø.76	8.89	1.11	1Ø.76
SKAM	45Ø	Ø.76	4.44	Ø.56	5.76
SKAM	6ØØ	Ø.76	3.33	Ø.42	4.51
SKAM	9ØØ	1.59	3.33	Ø.56	5.48
SKAM	12ØØ	1.59	2.5Ø	Ø.42	4.51
SKAM	15ØØ	1.95	2.ØØ	Ø.5Ø	4.45
SKAM	22ØØ	2.82	2.27	Ø.45	5.55
SKAM	3ØØØ	3.99	2.ØØ	Ø.42	6.4Ø
SKAM	37ØØ	4.4Ø	1.62	Ø.41	6.42
SKAM	45ØØ	5.74	1.78	Ø.39	7.91
SKMM	225	Ø.Ø4	Ø.ØØ	1.11	1.15
SKMM	45Ø	Ø.Ø4	Ø.ØØ	Ø.56	Ø.6Ø
SKMM	6ØØ	Ø.Ø4	Ø.ØØ	Ø.42	Ø.46
SKMM	9ØØ	Ø.Ø8	Ø.ØØ	Ø.56	Ø.63
SKMM	12ØØ	Ø.Ø8	Ø.ØØ	Ø.42	Ø.5Ø
SKMM	15ØØ	Ø.12	Ø.ØØ	Ø.5Ø	Ø.62
SKMM	22ØØ	Ø.16	Ø.ØØ	Ø.45	Ø.61
SKMM	3ØØØ	Ø.2Ø	Ø.ØØ	Ø.42	Ø.61
SKMM	37ØØ	Ø.24	Ø.ØØ	Ø.41	Ø.64
SKMM	45ØØ	Ø.28	Ø.ØØ	Ø.39	Ø.67

Table 7.4 (cont'd)

Unit Costs for Stacking Systems - Scale II

(£)

(Automatic Stacking) Q2: Q=10,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAA	225	12.82	22.22	1.39	36.43
SKAA	450	6.41	11.11	0.69	18.22
SKAA	600	6.41	10.00	0.52	16.93
SKAA	900	4.27	6.67	0.35	11.29
SKAA	1200	4.27	5.83	0.26	10.37
SKAA	1500	2.35	4.67	0.21	7.23
SKAA	2200	2.50	3.64	0.14	6.28
SKAA	3000	2.69	2.67	0.10	5.46
SKAA	3700	2.77	2.43	0.08	5.28
SKAA	4500	2.81	2.22	0.07	5.10
SKMA	225	14.04	26.67	1.39	42.10
SKMA	450	7.02	13.33	0.69	21.05
SKMA	600	7.02	11.67	0.52	19.21
SKMA	900	4.68	7.78	0.35	12.81
SKMA	1200	4.68	7.50	0.26	12.44
SKMA	1500	2.54	6.67	0.21	9.42
SKMA	2200	2.69	5.45	0.14	8.28
SKMA	3000	3.29	4.00	0.10	7.39
SKMA	3700	3.35	3.78	0.08	7.22
SKMA	4500	3.68	3.56	0.07	7.31

Table 7.4 (cont'd)

UNIT STACKING COSTS

(Manual Stacking)

Q2: Q=10,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAM	225	0.46	8.89	1.11	10.46
SKAM	450	0.23	4.44	0.56	5.23
SKAM	600	0.23	3.33	0.42	3.98
SKAM	900	0.32	3.33	0.56	4.21
SKAM	1200	0.32	2.50	0.42	3.23
SKAM	1500	0.19	2.00	0.50	2.69
SKAM	2200	0.28	2.27	0.45	3.01
SKAM	3000	0.40	2.00	0.42	2.82
SKAM	3700	0.44	1.62	0.41	2.47
SKAM	4500	0.57	1.78	0.39	2.74
SKMM	225	0.02	0.00	1.11	1.13
SKMM	450	0.01	0.00	0.56	0.57
SKMM	600	0.01	0.00	0.42	0.43
SKMM	900	0.02	0.00	0.56	0.57
SKMM	1200	0.02	0.00	0.42	0.43
SKMM	1500	0.01	0.00	0.50	0.51
SKMM	2200	0.02	0.00	0.45	0.47
SKMM	3000	0.02	0.00	0.42	0.44
SKMM	3700	0.02	0.00	0.41	0.43
SKMM	4500	0.03	0.00	0.39	0.42

Table 7.4 (cont'd)

Unit Costs for Stacking Systems - Scale III

(£)

(Automatic Stacking)

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAA	225	12.11	22.22	1.39	35.72
SKAA	450	6.41	11.11	0.69	18.22
SKAA	600	4.99	10.00	0.52	15.51
SKAA	900	3.56	6.67	0.35	10.58
SKAA	1200	2.85	5.83	0.26	8.94
SKAA	1500	2.35	4.67	0.21	7.23
SKAA	2200	1.67	3.64	0.14	5.45
SKAA	3000	1.79	2.67	0.10	4.56
SKAA	3700	1.84	2.43	0.08	4.36
SKAA	4500	0.94	2.22	0.07	3.23
SKMA	225	13.26	26.67	1.39	41.32
SKMA	450	7.02	13.33	0.69	21.05
SKMA	600	5.46	11.67	0.52	17.65
SKMA	900	3.90	7.78	0.35	12.03
SKMA	1200	3.12	7.50	0.26	10.88
SKMA	1500	2.54	6.67	0.21	9.42
SKMA	2200	1.79	5.45	0.14	7.39
SKMA	3000	2.19	4.00	0.10	6.30
SKMA	3700	2.23	3.78	0.08	6.10
SKMA	4500	1.23	3.56	0.07	4.85

Table 7.4 (cont'd)

UNIT STACKING COSTS

(Manual Stacking)

Q3: Q=30,000 gal/day

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAM	225	0.43	8.89	1.11	10.43
SKAM	450	0.23	4.44	0.56	5.23
SKAM	600	0.18	3.33	0.42	3.93
SKAM	900	0.26	3.33	0.56	4.15
SKAM	1200	0.21	2.50	0.42	3.13
SKAM	1500	0.19	2.00	0.50	2.69
SKAM	2200	0.19	2.27	0.45	2.92
SKAM	3000	0.27	2.00	0.42	2.68
SKAM	3700	0.29	1.62	0.41	2.32
SKAM	4500	0.19	1.78	0.39	2.36
SKMM	225	0.02	0.00	1.11	1.13
SKMM	450	0.01	0.00	0.56	0.57
SKMM	600	0.01	0.00	0.42	0.43
SKMM	900	0.01	0.00	0.56	0.57
SKMM	1200	0.01	0.00	0.42	0.43
SKMM	1500	0.01	0.00	0.50	0.51
SKMM	2200	0.01	0.00	0.45	0.47
SKMM	3000	0.01	0.00	0.42	0.43
SKMM	3700	0.02	0.00	0.41	0.42
SKMM	4500	0.01	0.00	0.39	0.40

easily be identified for the individual stages from the data provided. However, as pointed out before, it would be unrealistic to assume that the simple selection of the least cost alternative at each stage in the process would give the overall least cost plant technology.

From the above analysis it could be seen that the lowest unit costs for a particular output was determined not simply by the technology used but also by the capacity (rate etc.) at which it was used and the type of process (i.e. discrete, continuous for pasteurization). The costs associated with transferring from one set of conditions at one stage to another set at a subsequent stage must therefore be taken into account. A way must be found to find the overall least cost combination of technologies (and their capacities) at the plant level and to identify these technologies in different economic situations. This is done in the following section, using the technique of dynamic programming.

7.3 Plant Level Optimization

In order to construct the production and cost functions at the plant level, the technique of Dynamic Programming is used, so that in addition to optimal values, optimal policies may also be derived (see Chapter 4). Thus this optimization exercise provides information on the actual physical choices that are optimal under a given set of circumstances.

In this section the formulation of the problem for the application of D.P. is discussed first and this is followed by an explanation of the optimization procedure as it applies to this case. Finally the computation of the optimal solutions and determination of the optimal decisions is discussed.

7.3.1 The D.P. Formulation

The dairy process may be described as a naturally sequential process, in which the stages are ordered without feedback or loops (acyclic). Although the processing stream is mainly continuous (except for batch pasteurization) throughout the plant, the use of the concept of food engineering operations has provided a basis for disaggregation of the plant process into stages or sub-processes. In order to apply the D.P. technique, the appropriate stages and the states at each stage must be identified and the interrelationship between the states at the different stages must be understood so that the nature of the transition relationship can be specified. After defining the policy (set of decisions) and the objective function, the D.P. procedure may be carried out.

a) Identifying states, stages, decisions and transitions

The states must necessarily coincide with the groups of unit operations for which equipment systems are designed, since the decisions can be made only with regard to designed systems. The stages represent the decision nodes (see Chapter 4). For the pasteurizing plant four stages have been identified ($n = 1, \ldots, 4$). These are i) Reception, ii) Pasteurization, iii) Filling and iv) Stacking. The product flow is represented schematically as

Raw Milk → | Intake System | → | Pasteurizer System | → | Filler System | → | Stacker System | → Output

The decisions are made largely with respect to the type of equipment system and its capacity. Unlike the engineering process design problems for which the D.P. technique has been used[1] there is not much emphasis on decisions concerning temperature or extent of product conversion. The key decisions in the pasteurizing plant are taken to relate primarily to speed (or capacity) and to the nature of the process flow (i.e. discrete or continuous). For other dairy and food products, however, other decision variables may be relevant. An example of a D.P. application involving other types of decision variables for a chemical manufacturing process is included as Appendix 7.2.

The process is non-stationary and so the decisions made

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1 See Nemhauser (1966), Aris (1961).

at each stage depend on the particular stage reached in the process. The way in which one state at a given stage $n, (S_n)$ is transformed into another state at the following stage (S_{n+1}) depends also on the stage reached. The principle characteristics of the states, decisions and transition relationships are given below in relation to the individual stages. The stages are numbered in relation to product flow.

i) Stage 1 - Reception

There are two initial states $(r = 1,2)$ at this stage, $(S_1(r = 1,2))$. These refer to the container in which the raw milk is brought to the plant (tanker, can). These initial states, however, are not carried through to the other stages and so do not create a dimensionality problem[1]. The difference in the temperature of the milk arriving in the different containers is accounted for by adding the respective cooling costs to the other reception costs.

There are two decisions to be made at the initial stage for each of the initial states. These decisions concern 1) the selection of system technology and 2) the capacity (intake rate) at which the technology should be operated.

For this purpose, four intake technologies for cans have been identified and these have already been discussed in Section 7.2 above (Manual, Manually assisted, Mechanical and Automatic). For tankers, another four are recognized (in-line manual control; in-line auto control; load cell; and weighbridge). In addition, ten capacity levels have been

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1 After Stage 1, it does not matter whether the milk was brought to the plant in cans or in tankers. The overall dimension is not altered. Refer to Chapter 4 (Section (4.4).

considered ranging, in thousands of gallons per hour, from 1,000 to 10,000. Then in the decision vectors together there are in all, $M = 10 \times 4 = 40$ components for each of the $R = 2$ input states.

The incoming milk in bulk or in cans is now transformed into milk flowing from different input lines at different rates of flow. These are the state characteristics of the input to stage 2 (S_{n+1}).

ii) <u>Stage 2 - Pasteurization</u>

At the pasteurization stage, the decision is made once again with regard to type of technology (batch or continuous flow (HTST)) and the capacity of the process. At this stage 5 batch capacities and 10 HTST flow rates are defined, giving at Stage 2, $R = 15$ decision components.

The ability to choose different types of technologies (e.g. discrete vs. continuous) and different capacities of the process at the different stages, derives from the use of the buffer storage tank associated with the storage operation that takes place between the reception and pasteurization groups of operations.

For a product transferring from a batch to a continuous technology and vice versa, and from one flow rate to another, the minimum storage capacity required can be computed. This is the capacity that prevents overflow where a larger quantity of inputs goes into storage than that which is taken out in the same time period, at the other end. Where the outflow is greater in any time period than the inflow the minimum required capacity is that which prevents the process downstream (towards the final output end of the process) from trying to take output from an empty storage tank.

In addition a minimum storage capacity is necessary to insure against temporary breakdowns in the plant and this must also be allowed for (see Chapter 6, Section 6.2). This type of process engineering exercise is done in the area of engineering around variations[1].

The minimum storage capacity to even out flows is therefore jointly determined by the output states from stage 1 (S_2) and the decisions (D_2) that transform these states into the states (S_3) which represent the pasteurizing rates and nature of flow.

The output from stage 2 is described again in terms of the nature of the flow and the capacity of the process as a result of the decisions made at this stage.

iii) <u>Stage 3 - Filling and Casing</u>

The filling decisions for acting upon the pulsed/continuous supply from the pasteurization stage are made with respect to the type of filling technology for a choice of glass bottle filling, plastic bottle filling and carton filling, ranging from manual to automatic systems where the choice exists, and with respect to the capacity of the process. In addition, the decision on a manually assisted or fully mechanical process has to be made, particularly with respect to the casing operation that accompanies the filling and is considered jointly with it. Furthermore for bottles, the joint washing/filling technology has to be taken into account. In all, six alternative filling line technologies

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1 See Rudd & Watson (1968, pages 397-428).

are identified. Ten filling rates (process capacities) are considered for each technology. This gives a total of (10 × 6=) 60 decision components to be computed, with respect to 15 input states represented by the nature of the output from the pasteurizing stage.

Again, the transition from pasteurizer process capacities and output type (batch or continuous) to the process capacities of the ten filling speed choices is accomplished by use of an appropriate size of buffer storage capacity. The required storage capacity must be evaluated along with the process alternative.

The output states from the filling stage are therefore described in terms of the filling rates and filling line equipment systems.

iv) Stage 4 - Stacking and Loading

The decision at the stacking and loading stage relates simply to a straightforward choice between manual (2-wheel case trolley) and what may be described as "auto-mechanical" (Automatic stacking equipment with fork-lift-truck) systems.

The two alternatives must be evaluated with respect to the sixty input states from the filling stage. The type of filling - line technology and the rate of filling, determine the number of individual filling lines that have to be installed and consequently affect the stacking alternatives.

b) The Objective Function

The objective is to minimize costs. For the purpose of technology choice, the "appropriate"[1] technology is taken to be the least cost technology (combination of sub-process alternatives). Because of the flexibility built into the design of the optimization programme structure, with the factors of production described in physical terms, the decisions on appropriateness can be reflected in the relative prices given to the factors of production for the purpose of the analysis.

The objective function may be written in the usual D.P. formulation as,

$$f_N(S_N) = \min \left[h(S_N, D_N) + f_{n-1}(S_{n-1})\right]$$

subject to the transformation relationship

$$S_N = T_{D_n}(S_{n-1}).$$

The individual stage cost function,

$$h(S_N, D_N)$$

is computed for each stage to give a set of cost values associated with the input states and decisions made at each stage. The recursive procedure is carried out by computing the $g(S_n, D_n)$ $\left[= h(S_n, D_n) + f_{n-1}(S_{n-1})\right]$ until the final stage is reached to give the $f_N^*(S_N)$.

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1 This relates only to appropriate factor use once the product has been specified. The concept of appropriateness also extends to the wider context of product choice and overall resource use (see Chapter 1).

7.3.2 The Optimization Procedure

A principle feature of the optimization procedure is that the problem is worked backwards (i.e. in the opposite direction to the product flow). This is the usual practice for manufacturing process design problems to which D.P. has been applied (see example in Appendix 7.2). The use of the backward formulation allows the optimal contractions of policy to be worked forward in time or, in this case, in relation to the product flow. This has special implications for the built-in sensitivity analysis afforded by the D.P. formulation (see Chapter 4 (Section 4.4.1)).

In using the backward formulation, the stages, described in Section 7.3.1 above, are renumbered in a direction opposite to the product flow, so that stage N refers to the initial stage (reception). The final stage (stacking and loading) is therefore optimized first.

In following the optimization procedure discussed in Chapter 4, the return function is evaluated by successively evaluating the function for increasing numbers of stages. To reiterate, briefly, for the final stage recursive optimization function

$$f_N(S_N) = \min \left[h(S_N, D_N + f_{N-1}(S_{N-1})\right]$$

with

$$f_{N-1}(S_{N-1}) = \min \left[h(S_{N-1}, D_{N-1}) + f_{N-2}(S_{N-2})\right]$$

the first stage to be evaluated is

$$f_1(S_1) = \left[h(S_1, D_1)\right] ,$$

which in this case is the final output stage. Because of this, the values must be computed with respect to all the input states at that stage, since the optimal values from the higher numbered stages (upstream) have not yet been determined.

Following this, the two end stages are evaluated jointly as,

$$f_2(S_2) \;+\; \min \; h(S_2, D_2) + f_1(S_1, D_1)$$

and continuing until the overall function has been evaluated.

The computational procedure may be divided into two phases. The first, involves the computation of the individual stage cost functions, $h(S_n, D_n)$ followed by the recursive procedure to obtain optimal values over the decision components, for each input state component from stage 1 to stage N. In the second phase, the backtracking is done, in which the optimal policy (set of decisions) and states are identified, starting at stage N and moving toward stage 1 (i.e. in reverse order to the way the recursive procedure was carried out, and in the direction of the material flow).

In order to do the search for the optimal policy (backtracking) successfully, the optimal values over the m decision components and with respect to each of the r components of the input state vector, must be stored in the computer during the first phase, in a way that allows the decisions and states to be identified in the second phase (see Appendix 7.1).

An appropriate flowchart for the recursive procedure, adapted from Nemhauser (1966)[1], is presented as Figure 7.1. The state components at each stage are numbered 1, 2, ..., R and the decision components, 1, 2, ..., M. The individual stage costs $h_n(S_n, D_n)$ $n = 1, \ldots, N$, are found starting with $h_1(S_1, D_1)$ and from the second stage the composite function,

$$g_n = g\ h(S_n, D_n) \quad 0 \quad f_{n-1}(S_{n-1}),$$

is computed, where the operator 0 is in this case the positive sign (+) as the overall costs are assumed to be seperable additively.

When the computations have been done for all r values of S_n and all m values of D_n, taking into account the cumulative minimum up to that stage n, the minimum cost for each input state, $f(S_n = r) = \max g_n(S_n = r)$ is found over m for each r at that stage, and the values stored. When this cumulative optimization procedure has been completed for all stages to state N, the global optimum (lowest cost value) is selected, and it is from this value that the backward trace to find the optimal policy and states is done.

In this way, the optimal physical choices at each stage that give the overall lowest plant level unit cost of production for a given output quality, are simultaneously determined with the least cost value.

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1. See Nemhauser (1966, p. 70).

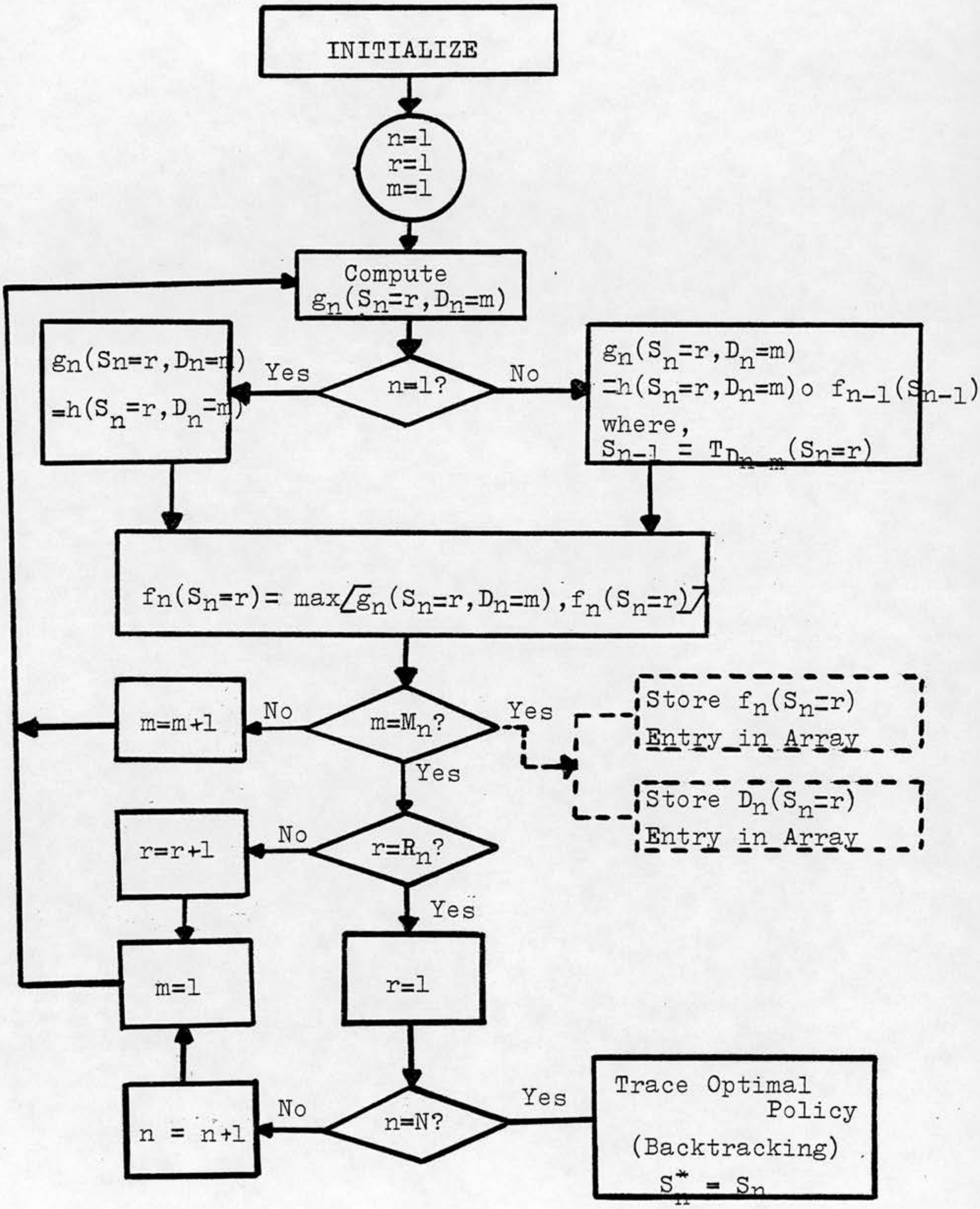

Figure 7.1 Flowchart for Dynamic Programming Computer Optimization

7.3.3 Plant Level Choices

The optimization procedure described in the previous sub-section was applied to the basic data, transforming the "physical" variables, with their values derived from the engineering relationships, into economic variables at the sub-process level and then recursively to the plant level. The FORTRAN coded programme and an example of the results at the plant level for one economic situation is provided as Appendix 7.1.

Because of the wide range of factor inputs being considered for economic evaluation, it is difficult to eliminate many alternatives solely on the basis of the physical quantities of the factors used. For the most part, this can only be done when the complex interrelationships of factor prices have been established for the particular economic situation under consideration. The programme, it may be noted, is designed to prompt for the appropriate unit values of a wide range of processing factors and material inputs (wages, interest, fuel, etc.,) which tend to be highly specific to the economic environment in which the plant operates.

The tabulated results attached to Appendix 7.1 illustrate the steps involved in the computation of the optimal (least cost) plant technology[1]. The tables show

i) the calculated basic unit costs for each stage derived from the physical relationships.

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1 Optimum combination of technologies for the groups of unit operations.

ii) the computed cost in relation to input states and decisions $(h(S_n, d_n))$ and

iii) the cumulative cost position $(g(S_n, d_n))$ worked recursively by adding the optimal values associated with the input states at the previously worked stage. The current optimal (minimum cost) values are given, optimizing over the decisions, for each input state.

iv) the final (cumulative) least cost position at the last worked stage (reception) with separate values for the two initial input states - can and tanker delivered milk.

The backtracking procedure to find the optimal policy (set of decisions) which, in this case, is the optimal plant technology, is done individually for the two initial input states starting at the final cumulative least cost value given.

Throughput volumes are not included as an additional state vector largely because of the problem of dimensionality[2]. The analysis can be done in relation to any single throughput volume by inserting the desired value as a run parameter. In this way a substantial saving in storage space on the computer can be effected.

The tabulated results in Appendix 7.1 may be used to demonstrate the way in which the optimal plant technology is found by carrying out the backtracking procedure. This is done with respect to each of the initial input states (can, tanker) for a small scale plant (1,000 gals/day throughput) in the hypothetical economy 1.

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1 See Chapter 4.

For can delivered milk, the optimal decisions and input states can be traced backwards from the final cumulative value for can reception through the cumulative D.P. tables $g(S_n, D_n)$. These choices are identified as follows:

i) the final global minimum for can received milk is the value associated with the decision to use the manual can technology (can 1) selecting an equipment capacity of 1,000 gallons per hour (slowest manual can reception technology). The cumulative value for this choice corresponds to the overall cumulative minimum (£210.82).

ii) with a reception rate of 1,000, and taking into account the effect of buffer storage on costs, the optimum decision at the pasturization stage (for optimum input rate of 1,000 gals/hr) is the High-Temperature-Short-Time (HTST) technology using an equipment capacity of 800 gallons per hour (HTTS) (cumulative value £154.16).

iii) at the filling stage, for an optimal input state of 800 gallons per hour with a continuous technology (HTST), the optimum filling decision, taking storage into account, is to use the "manual"[3] glass bottle filling technology (BOTM) at an equipment capacity of 225 gallons per hour (30 bottles/min.) (cumulative cost value £100.48).

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1 See Section 7.2.

iv) with an optimal input state characterised by a manual glass bottle filling technology at 225 gallons per hour capacity the optimal stacking decision is the manual stacking technology (SKMM) (cumulative cost value £0.60).

These optimal choices represent the nodes on the optimal path through the system based on the dynamic programming "principle of Optimality" (See Chapter 4 and Appendix 4.1). This means that the cost of any other combination can only be at best equal to, but not less than, the cost of this combination.

Thus, where the choices identified as optimal (least cost) with respect to individual stages considered independently (section 7.2 above), are different from those obtained via the D.P. Optimization procedure, the former must provide an inferior or, at best, equivalent solution to the plant level optimization problem.

The run results can be used to verify this, and it has been found that in many cases the optimal choice for the groups of operations (stages) considered independently are, indeed, different from those which belong to the optimal plant level combination. These differences are mainly related to the technical capacity of the processing system for that group of operations.

The tracing of the optimal decisions on technology can similarly be done for milk delivered by tanker. Using the same economic situation and daily throughput volume as for can reception (above), the optimal plant level combination is found to be:

In line metering with "manual" control (TNK 1) at capacity of 6,000 gallons per hour at reception; HTST pasteurization at a system capacity of 800 gallons per hour (HTTS) "manual" bottling in glass (BOTM) at 450 gallons per hour; manual stacking.

In this way, very precise details about the least cost plant level technological combination are obtainable with respect to each daily throughput volume to be considered. Using the least cost values churned out by this method a plant level cost curve can be described. As with the individual stage analysis (section 7.2), this curve is of the nature of the long-run curve in economic theory, since all factors are fully variable and each point on the curve can be construed as a point on a short-run (fixed equipment capacity) cost curve which represents the lowest total unit cost for the production of that input.

As with the individual stage analysis in the previous section, the implication of varying factor prices for optimal choice can be analysed. Table 7.5 shows the changing optimal choices with the different economic situations for three scales of operation (daily throughput quantities of 1,000, 10,000 and 30,000 gallons). The flexibility of the programme, however, allows the analysis to be done for any scale of operation. For this brief analysis only the relative prices of "capital", labour and electrical energy are varied according to the economic situations described in Section 7.2. The actual physical choices which are least cost at the plant

TABLE 7.5 (a)

OPTIMAL PLANT LEVEL CHOICES WITH FACTOR PRICE VARIATIONS - CAN RECEPTION

	S C A L E O F O P E R A T I O N S											
	1,000 gals/day				10,000 gals/day				30,000 gals/day			
Economy[1] / Group of Operations	E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4
1.RECEPTION[2]	C1 (1,000)	C1 (1,000)	C1 (1,000)	C2 (1,000)	C1 (3,000)	C3 (4,000)	C3 (4,000)	C3 (4,000)	C1 (4,000)	C3 (4,000)	C4 (9,000)	C3 (4,000)
2.PASTEURIZA-TION[3]	H5 (800)	H4 (500)	H5 (800)	H4 (500)	H10 (8,000)	H8 (3,000)	H9 (5,000)	H9 (5,000)	H10 (8,000)	H10 (8,000)	H10 (8,000)	H10 (8,000)
3.FILLING[4]	BM (225)	CM (450)	BM (450)	CM (450)	BM (1,500)	BMA (1,500)	BA (2,200)	BA (3,000)	BM (4,500)	BA (4,500)	BA (4,500)	BA (4,500)
4.STACKING[5]	MS	MS	MS	MS	MS	MS	AS	AS	MS	MS	AS	AS

NOTES:

1. The factor price variations are those listed for the four economic situations described in Section 7.2.
2. The four can reception technologies C1 - C4 are as described in Section 7.2
3. HT refers to the HTST System.
4. The first letter (B or C) refers to glass bottle and paper carton containers respectively. M, MA and A indicate "Manual", "Manually assisted" and Automatic technologies respectively. (see Sections 7.2.3 and 6.4.1.).
5. MS - Manual stacking; AS - "Automatic" stacking (see Section 7.2.4.).

TABLE 7.5 (b)

OPTIMAL PLANT LEVEL CHOICES WITH FACTOR PRICE VARIATIONS - TANKER RECEPTION

S C A L E   O F   O P E R A T I O N S

Economy[1] / Group of Operations	1,000 gals/day E1	E2	E3	E4	10,000 gals/day E1	E2	E3	E4	30,000 gals/day E1	E2	E3	E4
1. Reception[2]	T1 (6,000)	T1 (6,000)	T1 (6,000)	T1 (6,000)	T1 (8,000)	T1 (10,000)	T1 (8,000)	T1 10,000	T1 (8,000)	T1 10,000	T1 10,000	T1 10,000
2. Pasteur-ization[3]	HT5 (800)	HT3 (300)	HT5 (500)	HT4 (500)	HT10 (8,000)	HT8 (3,000)	HT10 (8,000)	HT8 (3,000)	HT10 (8,000)	HT9 (5,000)	HT10 (8,000)	HT9 (5,000)
3. Filling[4]	BM (450)	CM (225)	BM (450)	CM (450)	BM (1,500)	BM (1,500)	BA (2,200)	BA (2,200)	BM (4.500)	BA (4.500)	BA (4,500)	BA (4,500)
4. Stacking[5]	MS	MS	MS	MS	MS	MS	AS	AS	MS	MS	AS	AS

Notes:

1. See Note 1. Table 7.5 (a)
2. The four tanker reception technologies are described in Section 7.2
3. See Note 3, Table 7.5 (a)
4. See Note 4, Table 7.5 (a)
5. See Note 5, Table 7.5 (a)

level are easily identif ied with the factor price ratio determined, and all other possibilities on the production possibility surface can be ignored.

The more salient features of the plant level optimal technological combinations are broadly similar to those discussed in relation to the individual stages. These are mainly

i) the predominance of "manual" techologies (C1 & C2; BM & CM; MS) at the smallest scale considered (1,000 gallons/hr) even in the economic situation where the labour/capital ratio has been substantially increased (E3 & E4),

ii) the similar preponderance of mechanical and automated technologies (C3 & C4; BA; AS) at the larger end of the scale,

iii) the general cost advantage which the regenerative HTST continuous pasteurization system seems to have over the more typical "small scale" vat (batch) system, even at the smalles scale considered (1,000 gals/day).

One interesting feature of the results at the plant level is that an optimal combination can be composed of what are, in effect, different vintages of technology (e.g. the more traditional manual dumping of cans with the advanced HTST pasteurization). Furthermore, such combinations involve the simultaneous use of manual-and-machine-paced systems in a single plant, and illustrates the wide range of alternative combinations that can be found to be not only feasible but optimal when technology is disaggregated in this manner for plant level analysis.

In using this method, therefore, once the physical relationships between inputs and outputs have been defined for the systems available, the least cost combination for a given throughput volume (scale) can be expressed not only in terms of combinations of groups of factors, but also in terms of the actual alternative processing systems which are available.

In the final chapter, further attention is given to the implications of the analysis for giving answers to practical and theoretical problems and the advantages and limitations of the approach used in this paper for determining optimal technology choice.

CHAPTER 8

SUMMARY AND CONCLUSION

In concluding this thesis, the approach used and the results derived therefrom are subjected to a brief critical assessment of their value and potential for further extended application. In the first section, the implications for practical and theoretical analyses are examined. The limitations of the approach and the new directions into which it might be extended are also discussed. The final section summarizes the work done in the thesis.

8.1 Implications of the Study

The problem of finding a basis for choosing an optimal or "appropriate" technology for plant processes is generally considered as a practical one, and it is this type of problem to which this thesis is addressed. However, it is not easy to divorce the practical solutions from the theoretical issues to which they are related. The study has dealt with both these aspects and the implications are summarized below.

8.1.1 Implications for Technology Choice

By becoming familiar with the principles of food process engineering and by studying the basic processes used for carrying out the individual unit operations of food processing, it has been possible to identify a much wider range of alternative systems which have been designed to perform the respective individual operations.

In addition, the study of heat-transfer, fluid-flow and other engineering principles relevant to milk plant operation, along with assistance from equipment manufactures, has allowed the engineering factor inputs (in heat, pressure, etc.,) required for the various operations to be quantified with a rather high degree of precision. This has meant that several more physical or "intermediate" input variables (eg. primary fuel, electricity, man hours) are identified and quantified. With prices attached to these inputs, the components of "operating cost" are more closely defined so that, in addition to varying the price of labour and capital, the input prices for a wider range of operating inputs can be varied to provide a much stronger basis for the evaluation of the alternatives in different economic situations.

The use of the Dynamic Programming to discover the optimal technology policy at the plant level, has permitted the identity of the physical factors to remain intact as interrelationships are taken into account in the search for the least cost combination.

The approach used and the results derived have suggested the following about dairy processing and about the pasteurized milk products in particular:

i) even with the product (final or intermediate commodity) closely defined, there are still several alternative technological systems for producing that given product.

ii) although many new high technology systems are available (microprocessor intake, etc.,), less advanced more "manual"[1] type alternative systems from a different vintage are also simultaneously obtainable.

iii) the older vintage technologies do not all possess the same factor use characteristics, and so no generalization can be made about their appropriateness in any particular economic context. For example, manual can reception systems use a large quantity of labour units in output in relation to mechanical and automatic systems but use comparatively little of the other operating factors, motor energy in particular. On the other hand, the vat (batch) type pasteurization system which is of a similar vintage, not only requires comparatively more labour units than rival systems

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1. "Manual" in terms of the no. of labour units (labour hours) required to produce a given output.

but also consumes more thermal energy units (in particular), and floor space per output quantity because of the low heat transfer co-efficient of the system.

iv) many of the older technologies are manually paced (rate of operation limited by pace at which worker can perform his duty) and were designed for smaller scale operations. Scale-up is by replication of the entire system and so even where the system is optimal at small scale, the cost advantage can be quickly lost as the newer systems designed to accommodate higher capacities show strong increasing returns to factor use, (capital in particular).

v) an optimal plant level technology may be composed of different vintages of technology depending on the scale of operations and the relative factor prices. Thus, by being able to disaggregate the technology and take account of all the wide variety of inputs and their relative prices, optimal combinations are found which are such a "mixed bag" that they are unlikely to be offered as a typical standard package by an equipment supplier. In a study of technological choice by agro-based industries in the Carribbean by the author of this thesis (Whitehead, 1979), some local firms reported that substantial savings were made by "shopping around" for technology rather than accepting a whole package from a single supplier. Studies have shown, however, that multinational firms tend to use the same technology without regard to the economic environment or scale of plant in which they operate.[1]

vi) some of the more advanced technologies, which tend to be more economical in the use of labour, have also been found to be more economical in the use of some of the other factors especially thermal energy and floor space (e.g. H.T.S.T.) technology). It is important, therefore, that factor use be considered in its entirety so that a proper economic evaluation of the alternatives may be made for that particular economy. Many of the technology policy studies have concentrated on the quantity of labour used to the virtual exclusion of other operating inputs[2]. These other inputs are now included in the evaluation of the altervatives, to select the most "appropriate", using relative input prices (market of social) to reflect relative factor scarcities.

vii) the longer production runs are generally more economical in the use of some of the operating factors, especially labour and thermal energy units. Usually there is an initial or terminal labour requirement which is of the nature of a fixed cost

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1. See for example Morley and Smith, (1977)., Mason, (1973)., Yeoman, (1968).
2. See esp. C. S. Cooper et.al. (1975), D. Morawetz, (1974), "Park, (1974) (a), (1976)., J. Pickett et.al. (1974), F. Stewart, (1974) and contributions in A. S. Bhalla (ed.), (1975).

which is spread over the total throughput for the production run (e.g. labour activities at beginning and end of tanker delivery - see Chapter 6). For some processes using steam, there is often a certain quantity of steam that must initially be raised at the start of the process before a constant level is maintained across the processing run. This initial cost is spread over the entire production run.

In sum, then, the study has shown that it is difficult to make any generalizations about the vintage or character of technology which will be "appropriate" (i.e. least cost) in any given economic circumstance. The use of the relative factors vary considerably from one type of system design to another, and from one operation to another. A useful conclusion of the study is that it is of value to disaggregate plant technology and evaluate the alternatives to arrive at the more "appropriate" combination for the economic context in which the plant is to operate.

8.1.2. Theoretical Implications

The methods used in this thesis have been designed to allow technology choice to be analysed on the basis of the actual equipment and processing systems that have been designed, rather than on particular factor combinations which may not be strictly representative of any designed system available to potential producers. This approach, although adhering closely to the production function concept by specifying the relationship between factor inputs and output, does not involve reliance on the results of the standard analysis of optimal input combinations.

Nevertheless, the basic information generated for this analysis, easily lends itself to the more formal theoretical analysis and the testing of economic hypothesis on production and cost functions. This is particularly so with respect to the individual stage where the actual system alternatives can be represented by their factor input quantities to describe the points on an isoquant surface. By defining the marginal rate of technical substitution between any two factors and by specifying relative input prices, questions can be answered about the homogeneity of the production function and the elasticity of substitution of factor inputs as opposed to inputs of equipment and processing system technologies.

While it is feasible to use the data provided here for more formal analysis, it is much more practicable at the sub-process (or individual stage) level, where the number of alternatives are in more manageable proportions, than they are at the plant level. In order to relate all the possible factor input combinations to a given output quantity, the complete enumeration of all the possible combinations of single stage system alternatives would be necessary. In this case, complete enumeration would involve the consideration of alternatives in the magnitude of $2^{40} \times 10^{15} \times 15^{60} \times 20^{2}$[1]. The problem associated with enumeration of plant level alternatives has already been encountered in other studies[2] and the authors have responded by deleting certain alternatives from the analysis.

By applying the D.P. technique, as done in this thesis, the optimal factor combinations can be derived directly, once the factor prices have been specified. In this way, the points on the isocline showing the equality of the marginal rate of technical substitution with the price ratio along the expansion path are determined with respect to the factor combination associated with the overall plant level technology that has been found to be optimal for that output and set of factor price ratios. The cost curve is the locus of these optima.

The results of the analysis imply that, in general,

i) there are increasing returns to scale at the individual stage, and overall plant levels. Thus, the degree of homogeneity of the production function is less than unity and is therefore not of the Cobb-Douglas variety. Thus the derived cost curve (which includes <u>only</u> technical ecomomies) is downward sloping. As technical relationships alone are taken into account, the cost curve does not turn up but tends to become asymptotic to the X axis with higher levels of output. The curve

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1. See chapter 4.
2. See Kurz and Manne, (1973); David Livingstone Institute (1975)

levels out where larger capacity systems are no longer being designed and increased output is achieved through replication of existing systems.

ii) the capital scale exponent for equipment systems vary widely for different types of systems. For the newer systems designed for larger scale operations the scale cost factor is generally well below the 0.6 figure (0.3 - 0.5) which is often considered the useful rule-of-thumb[6] for capital cost estimation.

iii) the operating factors, for the most part, also increase less-than-proportionately with scale. This is true of labour and of thermal energy in particular, when these factors are attached to the more advanced types of equipment. For batch processes and some highly manual modes of operation, this is often not the case.

In general, the results produced by the use of the D.P. technique for plant level optimization can be used for more formal analysis of production and cost relationships, thereby obviating the need for the massive amount of computations required by a process of direct enumeration of the alternatives. The methods used here can therefore be extended even further in this direction.

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1. See Moore, (1959).

8.2. Summary

The decision to use the engineering production function approach to technology choice has been made on the basis of the perceived superiority of this approach relative to other approaches (see chapter 2) for the precise purpose of evaluating technological alternatives. The methods used are, however, not restricted to this purpose and are of value in the wider context of production and cost analyses.

The engineering approach starts from the conception of production as the application of energy to materials to effect some type of change in the material itself, in this case.

The plant process is represented by a set of unit operations through which the commodity (milk) passes in sequence, and at which energy is applied to transform the input commodity into an output commodity with a particular set of characteristics.

For each unit operation, the procedure of energy application requires a source of energy and an instrument of energy application. The source of energy may be animals (workers), primary fuels (coal, etc., for production of thermal energy), power (electric or water power for motor energy, etc.,), chemicals (for reaction to effect chemical changes, to transfer heat, etc.,). The instruments of energy application range from simple tools to the more sophisticated specialized machinery and equipment systems, and include boilers and generators. The instruments of energy application are those which are generally categorized as investment goods and become the economic fixed factor input "capital". The energy sources are the operating or variable factor inputs of which the animal source is the most familiar in economic analyses (labour).

This thesis, by using this engineering approach, places the other sources of energy in a much more central position than they have traditionally been held in standard empirical economic studies of production.

There are usually several ways in which these forms of energy may be combined to effect the required change and this is reflected in the design of the instruments used for applying the energy (equipment). In principle, then, certain underlying technical laws determine the possible system designs, and the range of alternatives (of energy sources and instruments). These could be quite extensive. In practice, however, only a few of the possibilities would actually have been designed. In this thesis the concern is only with the systems which have been designed.

The analysis, therefore, centres on the physical systems of instruments and their complimentary forms of energy which have been designed to perform a single unit operation of group of unit operations in the pasteurizing plant. In order to quantify the factors of production which must be costed for the subsequent economic evaluation of the alternatives, the analysis starts at what may be described as the engineering variables (heat, speed, etc.,), to which the cost of the instrument(s) and the various forms of energy can be related.

In order to identify and quantify the engineering variables and to relate them to the output capability per unit of time (capacity) of the designed system, many of the basic engineering principles and design laws have had to be called upon. The principles of thermodynamics (heat transfer) and hydraulics (fluid flow) have been of particular relevance to the process in the dairy plant. These laws, some arrived at experimentally, have provided a basis for evaluating the actual physical quantities of the different types of energy inputs associated with a particular system design. This, supplemented by information from equipment manufacturers and suppliers, allows the equipment systems to be represented by a set of variables to which costs can readily be attached, and to which output quantities can be directly related.

By using this engineering approach, the basic information on the relationship between inputs and outputs has much wider applicability as the analysis can more easily take place outwith any specific economic environment. The approach suffers from one drawback in this respect - the units in which the instruments (capital) must be expressed. This problem is, of course, not specific to this type of analysis but is one which has plagued many other studies in economics. Since it is virtually impossible to reduce all equipment systems to their basic material and energy inputs (eg. 1 cwt 18-18 stainless steel + 1,000 lbs. steam + 150 labour hours, Etc.,), it is necessary to express the instruments in money values. The use of equipment price indices and "appropriate" exchange ratios will extend the sphere of usefulness of the data (see chapter 6).

In addition to seeking greater applicability of the results, the study has sought to overcome some of the other drawbacks associated with earlier studies, in particular, the problem of taking the analysis from the level of individual stages to the plant level (see chapter 2). In this thesis, new ground is broken with the application of the Dynamic Programming Technique to the plant level optimization problem so that interrelationships between the choices made at the individual stages may be taken into account.

The results have generally supported the view that by disaggregating plant technology the range of feasible options open to producers can be expanded and allow more "appropriate" plant technologies to be identified. This is borne out by the technological mix that proved optimal in certain economic situations.

In general, the approach to technology choice used in this thesis, has been chosen for its flexibility which broadens the scope of the analysis and the application of the results. The alternative technologies included in the evaluation are permitted to range across the spectrum from the more traditional, through "intermediate", to the more advanced systems. In addition, the use of the basic "physical" relationships and the design of the optimization programme serve to substantially widen the area of applicability and to enhance the usefulness of the approach for providing answers for both practical and theoretical problems in production economics.

APPENDIX 4.1

The Principle of Optimality - A Proof

The Dynamic Programming Principle of Optimality on which this optimizing procedure is based, may be proven by a derivation of the basic functional equation

$$f_N(S_N) = \text{Min } [g(S_N, D_N) + f_{N-1}(S_N)].$$

Remembering that for a return function R:

$$\min_{D_1,\ldots,D_N} R = \min_{D_N} [\min_{D_1,\ldots,D_{N-1}} R]$$

Thus,

$$f_N(S_N) = \min_{D_1,\ldots,D_N} [g(S_N,D_N) + g(S_{N+1},D_{N-1}) + \ldots + g(S_1,D_1)]$$

$$= \min_{D_N} [\min_{D_1,\ldots,D_{N-1}} (g(S_N,D_N) + g(S_{N-1},D_{N-1}) + \ldots + g(S_1, D_1)]$$

$$= \min_{D_N} [g(S_N, D_N) + \min_{D_1,\ldots,D_{N-1}} (g(S_{N-1}, D_{N-1}) + \ldots + g(S_1, D_1)]$$

$$= \min_{D_N} [g(S_N, D_N) + f_{N+1}(S_{N-1})].$$

APPENDIX 5.1

Q U E S T I O N N A I R E

DAIRY EQUIPMENT MANUFACTURERS AND SUPPLIERS

QUESTIONNAIRE - NOTES

Please fill in the appropriate columns with data relevant to the equipment you supply to pasteurizing plants in the dairy industry only. Please write N.R. in the spaces where the question is not relevant to the type of equipment being considered, and N.A. where the information required is not available.

Notes to questions

Question 2 - In describing the model type, please indicate the most salient characteristic(s) by which the piece of equipment is usually identified for classification (e.g. for fillers - gravity, vacuum, etc.; for washers - straight through, rotary, soaker type, jet type, etc.) and, if possible, give the series code of the equipment (e.g. series B52 vacuum filler, etc.)

Questions 7,20 & 21 - Where motor horsepower is asked for, the KVA rating or wattage of the equipment may be given instead. Please specify which one of these is being used.

Questions 13 & 14 - In giving the scrap value and annual cost of spares assume there is no inflation over time.

Question 18 - The term 'previous work station' refers to the last work point from which the material has been conveyed to the point under consideration (e.g. for a bottle filler, the previous work station would be the bottle washer).

Question 23 - Please give, if possible, and where applicable, the costs per unit of other items which are to be used with the piece of equipment under consideration (e.g. cartons, bottles, cans, caps, detergent, cases, etc.).

If there should be any comments to be made concerning any of the information given (or not given), please use the reverse side of the questionnaire.

ame of

QUESTIONNAIRE

'irm........................

ECHNICAL SPECIFICATIONS & COSTS OF PASTEURIZED MILK PLANT EQUIPMENT

.. Capacity
2. Model Type
3. Basic cost (1980)
4. Installation cost
5. Pump capacity req'd
6. Cost of pump(s) (if not in (3) above
7. Motor Hp (or KVA)
8. Steam req'd per hour
9. Hot water req'd
10. Other water req'd
11. Floor space for unit
12. Expected useful life
13. Scrap value as % of initial cost
14. Annual cost of spares (as % of initial cost)
15. No. of men req'd for entire running time
16. No. of men req'd for part of running time
17. Skilled or supervisory personnel required
18. Conveyor type & length from previous work station (typical)
19. Conveyor cost
20. Conveyor motor Hp (KVA)
21. Compressed air per hour or air compressor Hp
22. Man hours req'd for maintenance annually (roughly - type of work)
23. Unit costs of accessories (Bottles, cans, cases, detergent, etc.- please list)

BULK RECEPTION SYSTEMS (COMPLETE) - FLOW METER SYSTEM									
A. GRAVITY FLOW SYSTEM					B. PUMP FLOW SYSTEM				
CAPACITY (GALLONS PER MINUTE)					CAPACITY (GALLONS PER MINUTE)				
Smallest	O t h e r			Largest	Smallest	O t h e r			Largest

C A N R E C E P T I O N S Y S T E M S (C O M P L E T E)								
A. AUTOMATIC TIPPING & RECORDING					B. MANUAL TIPPING, WEIGHING			
CAPACITY (CANS PER MINUTE)					CAPACITY (CANS PER MINUTE)			
mallest	O t h e r			Largest	Smallest	Other		Largest

C A N W A S H I N G								
A. AUTOMATIC CAN WASHING EQUIPMENT					B. MANUALLY ASSISTED WASHERS			
CAPACITY (CANS PER MINUTE)					CAPACITY (CANS PER MINUTE)			
Smallest	O t h e r			Largest	Smallest	Other		Largest

VAT (BATCH) PASTEURIZATION								
PRE-HEATING, PASTEURIZING AND COOLING BY BATCH (VAT) PROCESS								
CAPACITY (GALLONS PER BATCH AND TOTAL ELAPSED TIME FOR PROCESS)								
Smallest	Other Capacities							Largest

GLASS BOTTLE FILLERS (CONT'D)					BOTTLE INSPECTING EQUIPMENT			
B. HAND - OPERATED MODELS								
CAPACITY (BOTTLES PER MINUTE)					CAPACITY (BOTTLES PER MINUTE)			
Smallest	O t h e r			Largest	Smallest	Other		Largest

GLASS BOTTLE WASHING EQUIPMENT									
A. FULLY AUTOMATIC					B. MANUALLY ASSISTED				
CAPACITY (BOTTLES PER MINUTE)					CAPACITY (BOTTLES PER MINUTE)				
allest	O t h e r			Largest	Smallest	O t h e r			Largest

CASING AND UNCASING OF BOTTLES							CASE WASHER
A. CASE PACKING MACHINES			B. CASE UNPACKING MACHINES				CAPACITY
CAPACITY (CASES PER MINUTE)			CAPACITY (CASES PER MINUTE)				CASES/MINUTE
Smallest	O t h e r	Largest	Smallest	O t h e r		Largest	

CASE STACKING AND UNSTACKING									
A. CASE STACKING MACHINES					B. CASE UNSTACKING MACHINES				
CAPACITY (CASES PER MINUTE)					CAPACITY (CASES PER MINUTE)				
mallest	O t h e r			Largest	Smallest	O t h e r			Largest

APPENDIX 5.2

Q U E S T I O N N A I R E

DAIRY PROCESSING PLANTS

QUESTIONNAIRE

DAIRY MANUFACTURING TECHNOLOGY

PASTEURIZED MILK

NAME OF DAIRY .... INTERVIEWEE ....

DATE .... POSITION ....

Please indicate which unit of volume will be used throughout the questionnaire

a. Gallons ☐
b. Litres ☐

PART I

INPUT/OUTPUT

1. Quantity of raw milk intake per day ☐
2. Number of shifts per day ☐
3. Duration of each shift (give details) ....
   ....
4. Number of days worked per week ☐
5. Number of days worked per year ☐
6. Product combination of output. Please give details in the table below.

Product	Quantity Per day	Quantity Per week	No. of days of operation per year
1. Pasteurized milk (total)			
a. in bottles			
b. in paper cartons			
c. other			
2. Sterilized milk			
a. U.H.T.			
b. in cans			
c. in bottles			
3 Condensed/evaporated milk			
4. Flavoured milks			
5. Dried milk powder			
6. Yoghurt			
7. Cream			
8. Other			

PART II

PASTEURIZING TECHNOLOGY

Please fill in the appropriate columns with data relevant to your operations for pasteurized milk only. Ignore those questions which are not applicable to the equipment/machine system being considered.

Please give capacity figures in volume per hour. Consumption of energy and other services should be given in the relevant units either per hour or per 1,000 gallons (litres) of the product at that stage. Please specify which is being used.

In describing the equipment/machine (see row 1), please indicate the most salient characteristic by which the piece of equipment or machine is usually identified for classification. (e.g. for washer - soaker type, jet type, straight-through, rotary, etc. and for tank - silo, horizontal, etc.)

PASTEURIZED MILK ONLY

	1. RECEIVING Tanker Weigh bridge	Load cells	in-line meters
1. Description of equipment/ machine(s) - type			
2. Volume through equipment per day			
3. No. of days in use per week			
4. No. of equipment/machine units in use			
5. Capacity (size) of each unit			
6. Total capacity			
7. Operating capacity			
8. Total elapsed time for operation			
9. Labour req'd for entire duration of process			
10. Labour req'd for part of process time (details)			
11. Any special skills req'd			
12. No. of pumps req'd and pump capacity (each)			
13. Pump motor horsepower (each)			
14. Conveyor (type and length)			
15. Motor HP for conveyor			
16. Compressed air req'd			
17. Motor size for above			
18. Steam req'd (pounds/hour)			
19. Boiler horsepower for steam			
20. Hot water req'd			
21. Kilowatts for above			
22. Cooling medium			
23. Kilowatts for above			
24. Floor space for equipment			
25. Piping req'd			
26. Equipment Manufacturer/ supplier			
27. Ancilliary equipment (e.g. case dollies, bottles, etc.)			

R E C E I V I N G   C O N T ' D

C a n s

Manual Tipping & Recording	Power conveyor & recorder scale	Automatic receiving/ recording	Weigh tank	Dump tank	Can washer	

2. COOLING	3. Buffer Storage for Pasteurization	4. PASTEURIZATION			
Cooler	Storage Tanks	Batch	Continuous	H.T.S.T.	

5. FILTERING AND CLARIFYING			6. HOMOGENIZING	7. BUFFER STORAGE BEFORE PASTEURIZATION
In-line Filter	Clarifier	Clarifier/ Standardizer	Homogenizer	Storage Tanks

8. F I L L I N G

Glass Bottles		Cartons	Other	
Bottle Filler	Bottle Washer	Carton Filler	Containers	

9. CASING

Bottles (Glass)		Paper Bottles & Cartons			
Casing Machine	Manual Casing	Shrink Wrapper	Casing Machine	Manual Casing	

10. STACKING		11. CLEANING	
Mechanical Stacking	Manual Stacking	Manual Cleaning	Cleaned-in-Place

APPENDIX 7.1

Computer Optimization Programme and Results - Dynamic Programming Applied to Dairy Processing.

EDINBURGH FORTRAN(G) COMPILER VERSION 50.16

```
      PROGRAMME DAIRY
C     THIS IS THE BEGINNING OF STAGE 1 - CASING AND STACKING
      INTEGER I,J,K,L,M
      REAL  ILS,MRS,KWS,ILK,MRK,KWK,LEASTK,
     1LABCOSK,KCOST,MINFIL,
     1ILAB,LAB,LABH,LABCOS,KW
      DIMENSION BACK(40),MRK(40),KWK(40),TECHSK(4),SKTECH(20),
     3TECHK(40),CAPCOSK(40),LABCOSK(40),ENGCOSK(40),WATCOSK(40),
     4TETK(40),VARCOSK(40),KCOST(40),RATEK(40),FLSK(40),
     5TECHF(60),FTECH(6),COSTK(40),
     6LEASTK(20)
```

```
      CALL EMASFC('DEFINE',6,'26,STACK',8)
      CALL EMASFC('DEFINE',6,'27,STAKTEC',10)
      CALL EMASFC('DEFINE',6,'20,FILTEC',9)
      WRITE(6,500)
  500 FORMAT('SET RUN PARAMETERS')
      CALL FPRMPT('Q=:',3)
      READ(5,501)Q
  501 FORMAT(I2)
      CALL FPRMPT('GR=:',4)
      READ(5,503)GR
  503 FORMAT(F8.4)
      CALL FPRMPT('W=:',3)
      READ(5,504)W
  504 FORMAT(F6.2)
      CALL FPRMPT('E=:',3)
      READ(5,504)E
      CALL FPRMPT('WR=:',4)
      READ(5,503)WR
      CALL FPRMPT('FC=:',4)
      READ(5,504)FC
      CALL FPRMPT('R=:',3)
      READ(5,504)R
      CALL FPRMPT('H=:',3)
      READ(5,506)H
  506 FORMAT(F8.2)
      CALL FPRMPT('BOTLIF=:',8)
      READ(5,507)BOTLIF
  507 FORMAT(I2)
      CALL FPRMPT('BP=:',4)
      READ(5,508)BP
  508 FORMAT(F5.2)
```

```
      CALL FPRMPT('CARTCOS=: ',9)
      READ(5,509)CARTCOS
  509 FORMAT(F5.2)
      CALL FPRMPT('PBCOS=: ',7)
      READ(5,510)PBCOS
  510 FORMAT(F5.2)
      BOTCOS=BP/BOTLIF
      X=Q*1000
C     WRITE OUT RUN PARAMETERS
      WRITE(6,512)Q,X,GR,W,E,WR,FC,R,H
  512 FORMAT(//2X,I8,2X,I8,3X,8F8.4)
C    WRITE OUT STAGE HEADING
      WRITE(6,408)
  408 FORMAT(////25X,'THIS IS THE BEGINNING OF STAGE 1 - STACKING AND
     1LOADING - DAIRY')
C     READ IN RAW  DATA ON STACKING
      L=0
      DO 61 L=1,40
   61 READ(26,*)RATEK(L),BACK(L),KWK(L),MRK(L),FLSK(L)
C     DESCRIPTION OF STACKING TECHNOLOGY
      J=0
      READ(27,401)(TECHSK(J),J=1,4)
  401 FORMAT(A5/A5/A5/A5)
      M=0
      J=0
      K=0
      DO 29 J=1,4
      DO 9 K=1,10
      M=M+1
      TECHK(M)=TECHSK(J)
    9 CONTINUE
   29 CONTINUE
```

```
      READ(20,300)(FTECH(L),L=1,6)
  300 FORMAT(6A5)
C     EXPAND FILLING TECHNOLOGY FILE
      J=0
      M=0
      K=0
      DO 74 J=1,6
      DO 63 K=1,10
      M=M+1
      TECHF(M)=FTECH(J)
   63 CONTINUE
   74 CONTINUE
C     WRITE HEADINGS FOR STACKING COST DATA
      WRITE(6,402)
  402 FORMAT(///45X,'UNIT STACKING COSTS'//25X,
     1'TECHNOLOGY',4X,'RATE',6X,'CAPITAL',3X,'ELECTRICITY',3X,
     2'LABOUR',4X,'TOTAL COSTS')
C     COMPUTE STACKING COSTS FOR AUTO AND MANUAL FILLING
C     TECHNOLOGIES
      J=0
      DO 33 J=1,40
      TETK(J)=X/RATEK(J)
      IF(J .GT. 20) GO TO 64
      SP=BACK(J)*0.05
      GO TO 71
   64 SP=BACK(J)*0.01
   71 TET=TETK(J)
      LIFE=15
      SV=BACK(J)*0.05
      BAC=BACK(J)
      KW=KWK(J)
      LAB=MRK(J)
      FLS=FLSK(J)
```

```
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSK(J)=CAPCOS
      CALL ELECTRICITY(TET,KW,E,Q,ENGCOS)
      ENGCOSK(J)=ENGCOS
      CALL LABOUR2(TET,LAB,Q,W,LABCOS)
      LABCOSK(J)=LABCOS
      VARCOSK(J)=LABCOSK(J)+ENGCOSK(J)
      COSTK(J)=CAPCOSK(J)+VARCOSK(J)
C     WRITE OUT STACKING AVERAGE COST DATA
      WRITE(6,405)TECHK(J),RATEK(J),CAPCOSK(J),ENGCOSK(J),
     1LABCOSK(J),COSTK(J)
  405 FORMAT(/25X,A8,2X,I8,4F12.2)
   33 CONTINUE
C     SELECT LOWEST STACKING COSTS FOR AUTO AND FOR MANUAL FILLING
C     TECHNOLOGIES AND RATES
C     WRITE OUT HEADINGS
      WRITE(6,404)
  404 FORMAT(////45X,'DYNAMIC PROGRAMMING RESULTS'
     1///47X,'1-STAGE COSTS, (H(S1,D1)'//40X,'STACKING COSTS IN',
     11X,'RELATION TO FILLING INPUTS'//30X,
     1'OPT-TECHNOLOGY',5X,'RATE',5X,'AUTO-STACK',3X,'MANU-STACK'
     1,7X,'MINIMUM')
      DO 72 J=1,20
      M=J+20
      IF(COSTK(M).GT.COSTK(J)) GO TO 76
      LEASTK(J)=COSTK(M)
      SKTECH(J)=TECHK(M)
      GO TO 69
   76 LEASTK(J)=COSTK(J)
      SKTECH(J)=TECHK(J)
C     WRITE OUT RESULTS
   69 WRITE(6,403)SKTECH(J),RATEK(J),COSTK(J),COSTK(M),LEASTK(J)
  403 FORMAT(/30X,A8,6X,I8,5X,F8.2,5X,F8.2,8X,F8.2)
   72 CONTINUE
```

```
C     THIS IS THE BEGINNING OF STAGE 2 -FILLING STAGE
      REAL ILABF,MRF,KWF,LABCOSF
      DIMENSION  RATEF(60),BACF(60),MRF(60),KWF(60),WATF(60),
     1TETF(60),CAPCOSF(60),LABCOSF(60),ENGCOSF(60),WATCOSF(60),
     2VARCOSF(60),SCOSTS2(15,60),FUECOSF(60),OPTECHF(15),DUO(14),
     3FFCOST(15,60),FINCOSF(15,60),PTECH(15),COSTF(60),MINFIL(90),
     4OPTF(15),STEF(60),GASF(60),FLSF(60),CAPS(14),BACG(14),
     5FLSG(14),STCOST(15,10),STOREP(15,10),FUELCOS(60),FILTEC(90),
     6GASCOSF(60),PSTORE(15,10),LINE(60),FILCOST(90,10),PASTEC(90),
     1WRITEF(90,10),DOUB(14),ENGCOSG(14),CAPCOSG(14),CAPCOSS(14),
     2ENGCOSS(14)
      CALL EMASFC('DEFINE',6,'19,FILLING',10)
      CALL EMASFC('DEFINE',6,'22,PASTECH',10)
      CALL EMASFC('DEFINE',6,'23,STORAGE',10)
C     THIS IS THE DECLARATION FOR STAGE 3 - PASTEURIZATION STAGE
      REAL MRP,KWHP,ISP,NBR,KWG,INST,LABCOSP,KWP,INSTP
      DIMENSION RATE3(10),BS(5),TETB(5),BACB(5),HOLD(10),
     1MRP(15),KWP(15),WATP(15),BACP(15),STEP(15),RATEP(15),
     2NBR(15),TETP(15),LABCOSP(15),FUECOSP(15),INSTP(15),
     3CAPCOSP(15),TETC(15),ENGCOSP(15),WATCOSP(15),PCOST(15),
     4FPCOST(10,15),SCOSTS1(10,15),RATE2(10),VARCOSP(15),
     5FINCOSP(10,15),OPTP(10),ISP(15),FLSP(15),STORP(10,15),
     6RSTOREP(10,15),FINSTOR(10,15),RSTOR(10,15),KWG(14),CONTCOS(60)
      CALL EMASFC('DEFINE',6,'12,BATCH1',9)
      CALL EMASFC('DEFINE',6,'13,HTST',7)
      CALL EMASFC('DEFINE',6,'16,OUTR',7)
C     READ IN PASTEURIZATION DATA
C     READ IN RAW 'PHYSICAL' DATA FOR PASTEURIZATION USING BATCH
C     METHODS
      I=0
      DO 12 I=1,5
   12 READ(12,*)BS(I),TETB(I),BACP(I),MRP(I),KWP(I),STEP(I),FLSP(I)
C     READ IN RAW 'PHYSICAL' DATA FOR PASTEURIZATION USING
C     CONTINUOUS (& HTST) METHODS
```

```
      L=5
      DO 18 L=6,15
   18 READ(13,*)RATEP(L),BACP(L),MRP(L),KWP(L),INSTP(L),STEP(L),FLSP(L)
C     WRITE OUT STAGE HEADING
      WRITE(6,315)
C     BEGIN FILLING STAGE COMPUTATIONS
  315 FORMAT(////45X,'THIS IS THE BEGINNING OF STAGE 2 - FILLING')
C     READ IN RAW 'PHYSICAL' DATA FOR FILLING STAGE
      I=0
      DO 14 I=1,60
   14 READ(19,*)RATEF(I),LINE(I),BACF(I),KWF(I),MRF(I),
     1STEF(I),WATF(I),GASF(I),FLSF(I)
C     READ IN DATA ON STORAGE CAPACITIES
      L=0
      DO 21 L=1,14
   21 READ(23,*)CAPS(L),BACG(L),FLSG(L),KWG(L)
C     WRITE OUT HEADINGS FOR TABLE OF COST DATA FOR THE FILLING
C     STAGE
      WRITE(6,301)
  301 FORMAT(///60X,'UNIT FILLING COSTS',//20X,
     1'TECHNOLOGY',3X,'RATE',3X,'CAPITAL',2X,'ELECTRICITY',
     22X,'LABOUR',4X,'FUEL',4X,'WATER',3X,'CONTAINER',2X,
     1'TOTAL COSTS')
C     DO CONVERSION OF 'PHYSICAL' DATA TO AVERAGE COST DATA
      J=0
      DO 22 J=1,60
      TETF(J)=X/RATEF(J)
      IF(J.GT.30 .AND. J.LE.40)GO TO 27
      IF(J.GT.40)GO TO 94
      LIFE=15
      CONTCOS(J)=BOTCOS
      GO TO 31
```

```
   27 LIFE=10
      CONTCOS(J)=PBCOS
      GO TO 31
   94 LIFE=15
      CONTCOS(J)=CARTCOS
      GO TO 31
   31 TET=TETF(J)
      SV=BACF(J)*0.05
      SP=BACF(J)*0.05
      STEAM=STEF(J)
      KW=KWF(J)
      WAT=WATF(J)
      LAB=MRF(J)
      BAC=BACF(J)
      PS=1183
      GASS=GASF(J)
      FLS=FLSF(J)
      CALL  CAPITAL(LIFE, TET, FLS, BAC, SV, R, SP, Q, H, CAPCOS)
      CAPCOSF(J)=CAPCOS
      CALL   LABOUR2(TET, LAB, Q, W, LABCOS)
      LABCOSF(J)=LABCOS
      CALL   ELECTRICITY(TET, KW, E, Q, ENGCOS)
      ENGCOSF(J)=ENGCOS
      CALL  FUEL(TET, STEAM, PS, FC, Q, FUECOS)
      FUELCOS(J)=FUECOS
      CALL  GAS(TET, GASS, GR, Q, GASCOS)
      GASCOSF(J)=GASCOS
      FUECOSF(J)=FUELCOS(J)+GASCOSF(J)
      CALL  WATER(WAT, TET, WR, Q, WATCOS)
      WATCOSF(J)=WATCOS
      VARCOSF(J)=LABCOSF(J)+ENGCOSF(J)+FUECOSF(J)+WATCOSF(J)+CONTCOS(J)
      COSTF(J)=CAPCOSF(J)+VARCOSF(J)
```

```
C      WRITE OUT COST DATA FOR FILLING WITH THE VARIOUS TECHNOLOGIES
       WRITE(6,302)TECHF(J),RATEF(J),CAPCOSF(J),ENGCOSF(J),LABCOSF(J),
      1FUECOSF(J),WATCOSF(J),CONTCOS(J),COSTF(J)
  302 FORMAT(/19X,A8,4X,I6,1X,F8.2,3X,F8.2,3X,F8.2,2X,F6.2,3X,F6.2,
      12X,F8.2,4X,F8.2)
   22 CONTINUE
C      DYNAMIC PROGRAMMING FOR STAGE 2 STARTS HERE
C      COMPUTE THE EFFECTS OF PASTEURIZATION TYPES AND CAPACITIES ON
C      THE COSTS OF FILLING
C      WRITE OUT HEADING
       WRITE(6,305)
  305 FORMAT(////40X,'D.P.  FILLING COSTS,  (H(S1,D1)',//25X,'FILLING',
      11X,'COSTS IN RELATION TO INPUTS FROM PASTEURIZATION STAGE',//6X,
      1'PAST.TECH',2X, 'FILLER',3X,'RATE1',3X,'RATE2',3X,'RATE3',3X,
      1'RATE4',3X, 'RATE5',3X, 'RATE6',3X,'RATE7',3X,'RATE8',3X,'RATE9'
      1,3X,'RATE10')
C      READ IN DATA GIVING OUTPUT TYPES AND RATES FROM PASTEURIZATION
C      STAGE (PTECH)
       READ(22,311)(PTECH(J),J=1,15)
  311 FORMAT(10A5/5A5)
C      COMPUTE FINAL FILLING COSTS (FFCOSTS) WITH RESPECT TO
C      INPUT FROM PASTEURIZATION STAGE
C      ESTIMATE STORAGE COSTS
       J=0
       DO 84 J=1,15
       K=0
       DO 86 K=1,10
       IF(J.GT.5)GO TO 55
       RATEP(J)=BS(J)/TETB(J)
   55 IF(RATEP(J).EQ.RATEF(K)) GO TO 7
       IF(RATEP(J).LT.RATEF(K))GOTO 8
       PSTORE(J,K)=RATEP(J)-RATEF(K)
       GO TO 56
```

```
    7 PSTORE(J,K)=0.00
      GO TO 56
    8 PSTORE(J,K)=RATEF(K)-RATEP(J)
   56 TETP(J)=X/RATEP(J)
      STP4=RATEP(J)*1.5
      STORP(J,K)=PSTORE(J,K)*TETP(J)
      STOREP(J,K)=STP4+STORP(J,K)
      M=0
      DO 79 M=1,14
      IF(CAPS(M).GE.  STOREP(J,K)) GO TO 89
   79 CONTINUE
      M=0
      DO 68 M=1,14
      DOUB(M) = CAPS(M)*2
      IF(DOUB(M) .GE.  STOREP(J,K))GO TO 62
   68 CONTINUE
C     COMPUTE STORAGE COSTS
   62 SV=BACG(M)*2*0.05
      SP=BACG(M)*2*0.01
      KW=KWG(M)*2
      FLS=FLSG(M)*2
      BAC=BACG(M)*2
      GO TO 52
   89 SV=BACG(M)*0.05
      SP=BACG(M)*0.01
      KW=KWG(M)
      FLS=FLSG(M)
      BAC=BACG(M)
   52 LIFE=20
      TET=TETP(J)
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSG(M)=CAPCOS
      CALL ELECTRICITY(TET,KW,E,Q,ENGCOS)
      ENGCOSG(M)=ENGCOS
```

```
      STCOST(J,K)=CAPCOSG(M)+ENGCOSG(M)
   86 CONTINUE
   84 CONTINUE
C     ENLARGE STORAGE COST ARRAY TO ACCOMMODATE FILLING TECH
      M=0
      DO 25 J=1,15
      DO 39 K=1,60
      M=M+1
      SCOSTS2(J,K)=STCOST(J,M)
      IF(M.EQ.10) GO TO 35
      GO TO 39
   35 M=0
   39 CONTINUE
   25 CONTINUE
C     COMPUTE FINAL FILLING COSTS FOR INPUT RATES
      J=0
      DO 13 J=1,15
      K=0
      DO 77 K=1,60
      FFCOST(J,K)=SCOSTS2(J,K)+COSTF(K)
   77 CONTINUE
   13 CONTINUE
C     PREPARE DATA FOR WRITING OUT
      M=0
      DO 53 I=1,'15
      DO 70 J=1,60,10
      M=M+1
      L=J
      DO 46 K=1,10
      WRITEF(M,K)=FFCOST(I,L)
      L=L+1
   46 CONTINUE
      PASTEC(M)=PTECH(I)
      FILTEC(M)=TECHF(J)
   70 CONTINUE
   53 CONTINUE
```

```
      L=0
      DO 50 L=1,90
   50 WRITE(6,304)PASTEC(L),FILTEC(L),(WRITEF(L,K),K=1,10)
  304 FORMAT(/4X,A8,2X,A8,2X,10F8.2)
C     PERFORM 2-STAGE COMPUTATIONS
C     ADD OPTIMAL 1-STAGE COSTS FROM CASING AND STACKING
C     STAGE (LEASTK) TO COSTS AT FILLING STAGE (FFCOST)
      J=0
      L=0
      K=0
      DO 98 J=1,15
      DO 26 K=1,60
      L=L+1
      IF(K.GT.20 .AND. K.LT. 30) GO TO 57
      IF(K .GT. 50) GO TO 57
      FINCOSF(J,K) =FFCOST(J,K) + LEASTK(L)
      IF(L.EQ.10) GO TO 23
      GO TO 26
   57 M=L+10
      FINCOSF(J,K)=FFCOST(J,K)+LEASTK(M)
      IF(M.EQ.20)GO TO 23
      GO TO 26
   23 L=0
   26 CONTINUE
   98 CONTINUE
C     PREPARE FOR WRITE OUT
      M=0
      DO 90 I=1,15
      DO 34 J=1,60,10
      M=M+1
      L=J
      DO 48 K=1,10
      FILCOST(M,K)=FINCOSF(I,L)
```

```
      L=L+1
   48 CONTINUE
   34 CONTINUE
   90 CONTINUE
C     DETERMINATION OF 2-STAGE MINIMUM COSTS (OPTF) FOR EACH INPUT
C     TYPE AND CAPACITY FROM PASTEURIZATION STAGE AND FOR EACH
C     TYPE OF FILLING TECHNOLOGY
C     WRITE OUT HEADINGS
      WRITE (6,308)
  308 FORMAT(////45X,'DYNAMIC PROGRAMMING RESULTS',///50X,'2-STAGE COST
     1DATA',/55X,'G(S2,D2)',///6X,'PAST. TECH',1X,'FILLER',2X,'RATE1',
     13X,'RATE2',3X, 'RATE3',3X,'RATE4',3X,'RATE5',3X,'RATE6',3X,
     1'RATE7',3X,'RATE8',3X, 'RATE9',3X,'RATE10',2X,'MINIMUM')
      J=0
      DO 24 J=1,90
      K=1
      MINFIL(J)=FILCOST(J,K)
      DO 32 K=2,10
      IF(FILCOST(J,K).GE.MINFIL(J)) GO TO 32
      MINFIL(J)=FILCOST(J,K)
   32 CONTINUE
   24 CONTINUE
C     WRITE OUT RESULTS
      DO 19 J=1,90
   19 WRITE(6,303)PASTEC(J),FILTEC(J),(FILCOST(J,K),K=1,10),
     1MINFIL(J)
  303 FORMAT(/5X,A8,1X,A8,11F8.2)
C     SELECT AND STORE MINIMUM FILLING VALUES FOR EACH PAST
C     TECH
C     WRITE OUT HEADINGS
      WRITE(6,310)
  310 FORMAT(///45X,'OPTIMAL VALUES FOR STAGE 2',//35X,
     1'PAST.  TECH',8X,'FILLING TECH',10X,'OPTIMUM')
```

```
      L=0
      J=0
      DO 58 J=1,90,6
      L=L+1
      OPTF(L) = MINFIL(J)
      OPTECHF(L)=FILTEC(J)
      K=J
      M=1
      DO 38 M=2,6
      K=K+1
      IF(MINFIL(K).GE.OPTF(L)) GO TO 38
      OPTF(L)=MINFIL(K)
      OPTECHF(L)=FILTEC(K)
   38 CONTINUE
C     WRITE OUT OPTIMAL VALUES
      WRITE(6,400)PTECH(L),OPTECHF(L),OPTF(L)
  400 FORMAT(/35X,A8,10X,A8,12X,F8.2)
   58 CONTINUE
C     THIS IS THE BEGINING OF STAGE 3 - PASTEURIZATION STAGE
C     WRITE OUT HEADINGS FOR TABLE OF COST DATA FOR THE
C     PASTEURIZATION STAGE (TO INCLUDE BOTH BATCH AND
C     CONTINUOUS COSTS FOR THE GIVEN QUANTITY OF MILK
C     THROUGHPUT)
      WRITE(6,202)
  202 FORMAT(////45X,'UNIT PASTEURIZATION COSTS',
     1///20X,'TECHNOLOGY',6X,'CAPITAL',5X,'LABOUR',3X,
     2'ELECTRICITY',5X,'FUEL',2X,'TOTAL PAST. COSTS')
C     DO CONVERSION OF 'PHYSICAL' DATA TO AVERAGE COST DATA FOR BATCH
C     DATA AND HTST
      J=0
      DO 47 J=1,15
      IF(J.GT.5)GO TO 36
      NBR(J)=X/BS(J)
```

```
      TETP(J)=NBR(J)*TETB(J)
      LIFE=20
      SV=BACP(J)*0.01
      SP=BACP(J)*0.025
      GO TO 43
   36 TETP(J)=X/RATEP(J)
      LIFE=12
      SV=BACP(J)*0.03
      SP=BACP(J)*0.025
      INST=INSTP(J)
   43 FLS=FLSP(J)
      BAC=BACP(J)
      PS=1185
      STEAM=STEP(J)
      TET=TETP(J)
      LAB=MRP(J)
      KW=KWP(J)
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSP(J)=CAPCOS
      CALL LABOUR2(TET,LAB,Q,W,LABCOS)
      LABCOSP(J)=LABCOS
      CALL ELECTRICITY(TET,KW,E,Q,ENGCOS)
      ENGCOSP(J)=ENGCOS
      IF(J.GT.5)GO TO 93
      CALL FUEL(TET,STEAM,PS,FC,Q,FUECOS)
      FUECOSP(J)=FUECOS
      GO TO 91
   93 CALL FUEL2(TET,INST,STEAM,PS,FC,Q,FUECOS)
      FUECOSP(J)=FUECOS
   91 VARCOSP(J)=LABCOSP(J)+ENGCOSP(J)+FUECOSP(J)
      PCOST(J)=CAPCOSP(J)+VARCOSP(J)
C     WRITE OUT COST DATA FOR PASTEURIZATION WITH THE
C     VARIOUS TECHNOLOGIES
```

```
      WRITE(6,203)PTECH(J),CAPCOSP(J),LABCOSP(J),ENGCOSP(J),FUECOSP(J),
     1PCOST(J)
  203 FORMAT(/19X,A8,4X,5F12.2)
   47 CONTINUE
C     DYNAMIC PROGRAMMING ROUTINE STARTS HERE
C     COMPUTE PASTEURIZATION COSTS IN RELATION TO INPUT RATES
C     (FROM RECEPTION STAGE) TO FORM OVERALL COST MATRIX FROM WHICH
C     3-STAGE COSTS MAY BE DERIVED
C     READ IN DATA GIVING OUTPUT RATES FROM RECEPTION STAGE
      READ(16,*)(RATE2(L),L=1,10)
C     DO COMPUTATIONS AND ACCOUNT FOR THE WAY IN WHICH INPUT
C     RATES AFFECT THE COSTS OF BATCH AND CONTINUOUS PROCESSES
C     (LARGELY THROUGH EFFECT ON STORAGE TIME & COSTS)
C     WRITE OUT HEADING
      WRITE(6,205)
  205 FORMAT(////40X,'D.P.  PASTEURIZATION COSTS (H(S3,D3))',//25X,
     1'PASTEURIZATION COSTS  IN RELATION TO INPUT RATES FROM',
     11X,'RECEPTION STAGE',//4X,'INPUT RATE',2X,'BATCH1',1X,
     1'BATCH2', 1X,'BATCH3',1X,'BATCH4', 1X,'BATCH5',1X,'HTST1',2X,
     2'HTST2',2X,'HTST3',2X,'HTST4',2X,'HTST5',2X,'HTST6',2X,'HTST7'
     12X,'HTST8',3X, 'HTST9',2X,'HTST10')
      J=0
      DO 54 J=1,10
      K=0
      DO 66 K=1,15
      IF(K.GT.5)GOTO 28
      RATEP(K)=BS(K)/TETB(K)
   28 IF(RATE2(J) .EQ. RATEP(K))GO TO 3
      IF(RATE2(J) .LT.RATEP(K))GO TO 4
      RSTOREP(J,K)=RATE2(J)-RATEP(K)
      GO TO 2
    3 RSTOREP(J,K)=0.00
      GO TO 2
    4 RSTOREP(J,K)=RATEP(K)-RATE2(J)
```

```
      GO TO 2
    2 HOLD(J)=X/RATE2(J)
      STP3=RATE2(J)*1.5
      RSTOR(J,K)=RSTOREP(J,K)*HOLD(J)
      FINSTOR(J,K)=RSTOR(J,K)+STP3
      M=0
      DO 11 M=1,14
      IF(CAPS(M).GE.FINSTOR(J,K)) GO TO 49
   11 CONTINUE
      M=0
      DO 45 M=1,14
      DUO(M)=CAPS(M)*2
      IF(DUO(M).GE.FINSTOR(J,K)) GO TO 96
   45 CONTINUE
C     COMPUTE STORAGE COSTS
   96 SV=BACG(M)*2*0.05
      SP=BACG(M)*2*0.01
      FLS=FLSG(M)*2
      KW=KWG(M)*2
      BAC=BACG(M)*2
      GO TO 85
   49 SV=BACG(M)*0.05
      SP=BACG(M)*0.01
      FLS=FLSG(M)
      KW=KWG(M)
      BAC=BACG(M)
   85 LIFE=20
      TET=HOLD(J)
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSS(M)=CAPCOS
      TET=TET+TETP(K)
      CALL ELECTRICITY(TET,KW,E,Q,ENGCOS)
      ENGCOSS(M)=ENGCOS
```

```
      SCOSTS1(J,K)=CAPCOSS(M)+ENGCOSS(M)
      FPCOST(J,K)=PCOST(K)+SCOSTS1(J,K)
   66 CONTINUE
C     WRITE OUT COSTS
      WRITE(6,206)RATE2(J),(FPCOST(J,K),K=1,15)
  206 FORMAT(//5X,I8,2X,15F7.2)
   54 CONTINUE
C     WRITE OUT HEADINGS FOR 3-STAGE COST DATA
      WRITE(6,204)
  204 FORMAT(////50X,'DYNAMIC PROGRAMMING RESULTS',
     1///55X,'3-STAGE COST DATA',/60X,'G(S3,D3)',//1X,'RECEPTION  RATE'
     1,1X,'BATCH1', 1X,'BATCH2',1X,'BATCH3',1X,'BATCH4',1X,'BATCH5',2X,
     3'HTST1',2X,'HTST2',2X,'HTST3',2X,'HTST4',2X,
     4'HTST5',2X,'HTST6',2X,'HTST7',2X,'HTST8',2X,'HTST9',2X,
     5'HTST10',2X,'MINIMUM')
C     PERFORM 3-STAGE COMPUTATIONS
C     ADD OPTIMAL 2-STAGE COSTS FROM FILLING STAGE (OPTF) TO
C     COSTS AT PASTEURIZATION STAGE
      J=0
      DO 73 J=1,10
      K=0
      DO 78 K=1,15
      FINCOSP(J,K)=FPCOST(J,K)+OPTF(K)
   78 CONTINUE
   73 CONTINUE
C     DETERMINATION OF 3-STAGE MINIMUM COSTS (OPTP) FOR
C     EACH INPUT RATE
      L=0
      DO 30 L=1,10
      OPTP(L)=FINCOSP(L,1)
      M=1
      DO 92 M=2,15
      IF(FINCOSP(L,M).GT.OPTP(L))GO TO 92
      OPTP(L)=FINCOSP(L,M)
```

```
   92 CONTINUE
   30 CONTINUE
C     WRITE OUT 3-STAGE COSTS
      J=0
      DO 88 J=1,10
   88 WRITE(6,209)RATE2(J),(FINCOSP(J,K),K=1,15),OPTP(J)
  209 FORMAT(//4X,I6,6X,15F7.2,3X,F7.2)
C     THIS IS THE BEGINING OF STAGE 4
      INTEGER ICOMPU
      REAL ILABR,LABHR,KWHR,LEAST1,LEAST2,LABCOSR
      DIMENSION BACR(80),ILABR(80),LABHR(80),KWHR(80),WATR(80),
     1RATE1(80),CAPCOSR(80),STER(80),
     1LABCOSR(80),ENGCOSR(80),WATCOSR(80),TETR(80),TOTCOSR(80),
     1FLSR(80),
     1VARCOSR(80),RCOST(8,10),UNCAP(80),FUECOSR(80),
     1FINCOSR(8,10),OPTR(8),TECHR(8),TECH(80)
      CALL EMASFC('DEFINE',6,'10,RECEPT',9)
      CALL EMASFC('DEFINE',6,'8,RECEP',7)
C     WRITE OUT STAGE HEADING
      WRITE(6,102)
  102 FORMAT(////45X,'THIS IS THE BEGINNING OF STAGE 4 - RECEPTION')
C     READ IN DATA
      I=0
      DO 10 I=1,80
   10 READ(10,*)RATE1(I),BACR(I),KWHR(I),ILABR(I),LABHR(I),STER(I),
     1WATR(I),
     1FLSR(I)
C     READ IN DATA ON RECEPTION TECHNOLOGY
      READ(8,118)(TECHR(L),L=1,8)
  118 FORMAT(8A5)
C
C     EXPAND INPUT TECH FILE
      M=0
      DO 59 J=1,8
      DO 60 K=1,10
```

```
      M=M+1
      TECH(M)=TECHR(J)
   60 CONTINUE
   59 CONTINUE
C     WRITE OUT HEADINGS
      WRITE(6,100)
  100 FORMAT(///55X,'UNIT RECEPTION COSTS',///20X,'TECHNOLOGY',
     15X,'RATE PER HOUR',3X,'CAPITAL',3X,'ELECTRICITY',4X,'LABOUR',6X,
     1'FUEL',7X,'WATER',3X, 'RECEPTION COSTS')
C     DO CONVERSION OF 'PHYSICAL' DATA TO AVERAGE COST DATA
      J=0
      DO 15 J=1,80
      TETR(J)=X/RATE1(J)
      TET=TETR(J)
      STEAM=STER(J)
      ILAB=ILABR(J)
      LAB=LABHR(J)
      FLS=FLSR(J)
      BAC=BACR(J)
      PS=1183
      KW=KWHR(J)
      WAT=WATR(J)
      IF(J.GT.40)GO TO 83
      LIFE=10
      SV=BACR(J)*.01
      SP=BACR(J)*.05
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSR(J)=CAPCOS
      GO TO 17
   83 LIFE=15
      SV=BACR(J)*.03
      IF(J.GT.50.AND.J.LE.60)GO TO 87
      SP=BACR(J)*0.05
```

```
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSR(J)=CAPCOS
      GO TO 17
   87 SP=BACR(J)*0.15
      CALL CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      CAPCOSR(J)=CAPCOS
   17 CALL LABOUR1(TET,ILAB,LAB,Q,W,LABCOS)
      LABCOSR(J)=LABCOS
      CALL ELECTRICITY(TET,KW,E,Q,ENGCOS)
      ENGCOSR(J)=ENGCOS
      CALL FUEL(TET,STEAM,PS,FC,Q,FUECOS)
      FUECOSR(J)=FUECOS
      CALL WATER(WAT,TET,WR,Q,WATCOS)
      WATCOSR(J)=WATCOS
      VARCOSR(J)=ENGCOSR(J)+LABCOSR(J)+FUECOSR(J)+WATCOSR(J)
      TOTCOSR(J)=CAPCOSR(J)+VARCOSR(J)
      WRITE(6,101)TECH(J),RATE1(J),CAPCOSR(J),ENGCOSR(J),LABCOSR(J),
     1FUECOSR(J),WATCOSR(J), TOTCOSR(J)
  101 FORMAT(/20X,A8,6X,I8,3X,6F12.2)
   15 CONTINUE
C     WRITE OUT HEADINGS FOR TABLE TO SHOW COSTS FOR THE VARIOUS
C     RECEPTION TECHNOLOGIES AT THE RATES BEING CONSIDERED
      WRITE(6,110)
  110 FORMAT(////45X,'D.P. RECEPTION COSTS (H(S1,D1))',//40X,
     1'RECEPTION COSTS IN RELATION TO INPUT STATES',///20X,'TECHNOLOGY',
     14X, '1000',4X,'2000',4X,'3000',4X,'4000',4X,'5000'4X,'6000',
     14X,'7000',4X,'8000',4X,'9000',3X,'10000')
C     DETERMINE COSTS FOR ALL TECHNOLOGIES FOR ALL RECEPTION RATES
      J=0
      K=0
      M=0
      L=0
      DO 20 J=1,80,10
```

```
      L=L+1
      DO 37 K=1,10
      M=M+1
      RCOST(L,K)=TOTCOSR(M)
   37 CONTINUE
   20 CONTINUE
C     WRITE OUT RECEPTION STAGE COST DATA IN FULL
      L=0
      DO 65 L=1,8
      WRITE(6,112)TECHR(L),(RCOST(L,K),K=1,10)
  112 FORMAT(//20X,A8,4X,10F8.2)
   65 CONTINUE
C     DYNAMIC PROGRAMMING ROUTINE STARTS HERE
C     ADD MINIMUM COST FOR RESPECTIVE RATE FROM PASTEURIZATION
C     STAGE TO RECEPTION STAGE COSTS
C     WRITE OUT HEADINGS FOR 4-STAGE COST DATA
      WRITE(6,108)
  108 FORMAT(////50X,'DYNAMIC PROGRAMMING RESULTS',
     1//55X,'4-STAGE COST DATA',/60X,'G(S4,D4)',//20X,'TECHNOLOGY',
     13X,'1000',3X,'2000',3X,'3000',3X,'4000',3X,'5000',
     13X,'6000',3X,'7000',3X,'8000',3X,'9000',3X,'10000',3X,'MINIMUM')
C     PERFORM 4-STAGE CALCULATIONS
      J=0
      DO 80 J=1,8
      K=0
      DO 81 K=1,10
      FINCOSR(J,K)=RCOST(J,K)+OPTP(K)
   81 CONTINUE
   80 CONTINUE
C     DETERMINATION OF FINAL 4-STAGE MINIMUM COST FOR EACH RECEPTION
C     TECHNOLOGY
      L=0
      DO 95 L=1,8
      OPTR(L)=FINCOSR(L,1)
```

```
      M=1
      DO 99 M=2,10
      IF(FINCOSR(L,M).GT.OPTR(L))GO TO 99
      OPTR(L)=FINCOSR(L,M)
   99 CONTINUE
   95 CONTINUE
C     WRITE OUT 4-STAGE COSTS
      DO 42 J=1,8
   42 WRITE(6,115)TECHR(J),(FINCOSR(J,K),K=1,10),OPTR(J)
  115 FORMAT(//18X,A8,5X,10F7.2,2X,F7.2)
C     DETERMINATION OF GLOBAL OPTIMUM
C     WRITE OUT FINAL HEADING
      WRITE(6,116)
  116 FORMAT(///35X,'THIS IS THE OVERALL LOWEST UNIT COST OF PRODUCTION'
     1//39X,'CAN RECEPTION',15X,'TANKER RECEPTION')
     J=1
      LEAST1=OPTR(J)
      DO 97 J=2,8
      IF(J.EQ.5)GO TO 40
      IF(J.GT.5) GO TO 41
      IF(OPTR(J).GT.LEAST1)GO TO 97
      LEAST1=OPTR(J)
      GO TO 97
   40 LEAST2=OPTR(J)
      GO TO 97
   41 IF(OPTR(J).GT.LEAST2)GO TO 97
      LEAST2=OPTR(J)
   97 CONTINUE
      WRITE(6,117)LEAST1,LEAST2
  117 FORMAT(///40X,F9.2,20X,F9.2)
      STOP
      END
```

```
      SUBROUTINE LABOUR1(TET,ILAB,LAB,Q,W,LABCOS)
      REAL ILAB,LAB,LABCOS
      IF (TET .GT.8)GO TO 19
      GO TO 18
   19 T=TET/8
      IT=T+1
      ILAB=ILAB*IT
   18 CALC=ILAB/Q
      CAL1=CALC*W
      CAL2=LAB*TET*W
      CAL3=CAL2/Q
      LABCOS=CAL1+CAL3
      RETURN
      END


      SUBROUTINE LABOUR2(TET,LAB,Q,W,LABCOS)
      REAL LAB,LABCOS
      CAL2=LAB*TET*W
      LABCOS=CAL2/Q
      RETURN
      END
```

```
      SUBROUTINE CAPITAL(LIFE,TET,FLS,BAC,SV,R,SP,Q,H,CAPCOS)
      A=1+R
      B=A**LIFE
      C=B-1
      D=R/C
      G=D+R
      BCOS=FLS*H
      P=A**50
      S=P-1
      T=R/S
      V=T+R
      BDEP=BCOS*V
      CVAL=BAC-SV
      DEP=CVAL*G
      ANCOS=DEP+BDEP+SP
      UNCAP=ANCOS/Q
      CAPCOS=UNCAP/312
      IF (TET.GT.8)GO TO 15
      GO TO 16
   15 T=TET/8
      IT=T+1
      CAPCOS=CAPCOS*IT
   16 RETURN
      END
```

```
      SUBROUTINE FUEL(TET,STEAM,PS,FC,Q,FUECOS)
      REAL LBF
      DEN=11000*0.8
      HOT=PS/DEN
      LBF=STEAM*HOT*TET*FC
      FUECOS=LBF/Q
      RETURN
      END


      SUBROUTINE FUEL2(TET,INST,STEAM,PS,FC,Q,FUECOS)
      REAL LBF,LBF1,LBF2,INST
      DEN=11000*.8
      HOT=PS/DEN
      LBF1=INST*HOT*FC
      LBF2=STEAM*HOT*FC
      IF (TET .GT. 8)GO TO 19
      GO TO 21
   19 T=TET/8
      IT=T+1
      LBF2=LBF2*IT
   21 LBF=LBF1+LBF2
      FUECOS=LBF/Q
      RETURN
      END
```

```
      SUBROUTINE ELECTRICITY(TET,KW,E,Q,ENGCOS)
      REAL KW
      ENG=KW*TET*E
      ENGCOS=ENG/Q
      RETURN
      END


      SUBROUTINE WATER(WAT,TET,WR,Q,WATCOS)
      WATC=WAT*TET*WR
      WATCOS=WATC/Q
      RETURN
      END


      SUBROUTINE GAS(TET,GASS,GR,Q,GASCOS)
      GASC=GASS*TET*GR
      GASCOS=GASC/Q
      RETURN
      END
```

```
CODE    25298 BYTES       PLT + DATA    47856 BYTES
STACK    3256 BYTES       DIAG TABLES    2772 BYTES       TOTAL  79182 BYTES
COMPILATION SUCCESSFUL


040611 MILK1 34K LISTED T15 LP15

***EMAS 2980 EMAS*** EJAA25 J.Whitehead       J.C.M.B.LEVELTHREE        END 05/08/81 22.42.31 EJAA2
***EMAS 2980 EMAS*** EJAA25 J.Whitehead       J.C.M.B.LEVELTHREE        END 05/08/81 22.42.31 EJAA2
***EMAS 2980 EMAS*** EJAA25 J.Whitehead       J.C.M.B.LEVELTHREE        END 05/08/81 22.42.31 EJAA2
***EMAS 2980 EMAS*** EJAA25 J.Whitehead       J.C.M.B.LEVELTHREE        END 05/08/81 22.42.31 EJAA2
***EMAS 2980 EMAS*** EJAA25 J.Whitehead       J.C.M.B.LEVELTHREE        END 05/08/81 22.42.31 EJAA2
```

APPENDIX 7.1 (Cont'd)

A sample of the output generated by Dynamic Programming Computer Optimization Programme Listed (Pasteurizing Plant in Economy 1, Q= 1000 gals/day).

SET RUN PARAMETERS

THIS IS THE BEGINNING OF STAGE 1 - STACKING AND LOADING - DAIRY3

UNIT STACKING COSTS

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAA	225	21.37	22.22	1.39	44.98
SKAA	450	21.37	11.11	0.69	33.18
SKAA	600	21.37	10.00	0.52	31.89
SKAA	900	21.37	6.67	0.35	28.38
SKAA	1200	21.37	5.83	0.26	27.46
SKAA	1500	23.53	4.67	0.21	28.40
SKAA	2200	25.04	3.64	0.14	28.81
SKAA	3000	26.85	2.67	0.10	29.62
SKAA	3700	27.66	2.43	0.08	30.18
SKAA	4500	28.12	2.22	0.07	30.41
SKMA	225	23.40	26.67	1.39	51.46
SKMA	450	23.40	13.33	0.69	37.43
SKMA	600	23.40	11.67	0.52	35.59
SKMA	900	23.40	7.78	0.35	31.53
SKMA	1200	23.40	7.50	0.26	31.16
SKMA	1500	25.43	6.67	0.21	32.31
SKMA	2200	26.87	5.45	0.14	32.47
SKMA	3000	32.90	4.00	0.10	37.01
SKMA	3700	33.49	3.78	0.08	37.36
SKMA	4500	36.84	3.56	0.07	40.46

UNIT STACKING COSTS

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	TOTAL COSTS
SKAM	225	0.76	8.89	1.11	10.76
SKAM	450	0.76	4.44	0.56	5.76
SKAM	600	0.76	3.33	0.42	4.51
SKAM	900	1.59	3.33	0.56	5.48
SKAM	1200	1.59	2.50	0.42	4.51
SKAM	1500	1.95	2.00	0.50	4.45
SKAM	2200	2.82	2.27	0.45	5.55
SKAM	3000	3.99	2.00	0.42	6.40
SKAM	3700	4.40	1.62	0.41	6.42
SKAM	4500	5.74	1.78	0.39	7.91
SKMM	225	0.04	0.00	1.11	1.15
SKMM	450	0.04	0.00	0.56	0.60
SKMM	600	0.04	0.00	0.42	0.46
SKMM	900	0.08	0.00	0.56	0.63
SKMM	1200	0.08	0.00	0.42	0.50
SKMM	1500	0.12	0.00	0.50	0.62
SKMM	2200	0.16	0.00	0.45	0.61
SKMM	3000	0.20	0.00	0.42	0.61
SKMM	3700	0.24	0.00	0.41	0.64
SKMM	4500	0.28	0.00	0.39	0.67

DYNAMIC PROGRAMMING RESULTS

1-STAGE COSTS, (H(S1,D1)

STACKING COSTS IN RELATION TO FILLING INPUTS

OPT-TECHNOLOGY	RATE	AUTO-STACK	MANU-STACK	MINIMUM
SKAM	225	44.98	10.76	10.76
SKAM	450	33.18	5.76	5.76
SKAM	600	31.89	4.51	4.51
SKAM	900	28.38	5.48	5.48
SKAM	1200	27.46	4.51	4.51
SKAM	1500	28.40	4.45	4.45
SKAM	2200	28.81	5.55	5.55
SKAM	3000	29.62	6.40	6.40
SKAM	3700	30.18	6.42	6.42
SKAM	4500	30.41	7.91	7.91
SKMM	225	51.46	1.15	1.15
SKMM	450	37.43	0.60	0.60
SKMM	600	35.59	0.46	0.46
SKMM	900	31.53	0.63	0.63
SKMM	1200	31.16	0.50	0.50
SKMM	1500	32.31	0.62	0.62
SKMM	2200	32.47	0.61	0.61
SKMM	3000	37.01	0.61	0.61
SKMM	3700	37.36	0.64	0.64
SKMM	4500	40.46	0.67	0.67

THIS IS THE BEGINNING OF STAGE 2 - FILLING

UNIT FILLING COSTS

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
BOTM	225	41.09	24.89	4.56	7.44	0.74	0.55	79.27
BOTM	450	51.95	20.00	2.83	7.44	0.50	0.55	83.27
BOTM	600	65.96	18.00	2.96	7.31	0.40	0.55	95.17
BOTM	900	77.05	16.22	2.81	7.51	0.38	0.55	104.52
BOTM	1200	92.18	15.67	2.52	6.30	0.38	0.55	117.59
BOTM	1500	115.24	17.47	2.50	7.36	0.42	0.55	143.52
BOTM	2200	148.49	16.73	2.39	6.21	0.39	0.55	174.75
BOTM	3000	197.40	14.53	2.25	6.08	0.38	0.55	221.19
BOTM	3700	277.98	14.05	2.30	5.95	0.37	0.55	301.21
BOTM	4500	328.85	13.47	2.22	5.79	0.36	0.55	351.24
BOMA	225	44.66	72.89	2.22	13.30	1.07	0.55	134.69
BOMA	450	53.75	40.89	1.11	9.74	0.63	0.55	106.66
BOMA	600	65.99	37.33	1.25	8.72	0.47	0.55	114.31
BOMA	900	75.32	31.56	1.39	8.03	0.40	0.55	117.25
BOMA	1200	87.70	33.33	1.04	6.95	0.47	0.55	130.05
BOMA	1500	107.23	30.00	1.00	7.63	0.47	0.55	146.88
BOMA	2200	134.20	25.91	0.91	5.99	0.41	0.55	167.97
BOMA	3000	178.87	28.00	0.83	6.51	0.41	0.55	215.17
BOMA	3700	253.51	26.49	0.88	6.06	0.37	0.55	287.86
BOMA	4500	297.61	24.89	0.83	5.93	0.37	0.55	330.18
BOTA	225	70.39	92.44	1.39	19.48	1.26	0.55	185.51
BOTA	450	71.61	46.22	0.69	9.74	0.63	0.55	129.44
BOTA	600	99.47	54.00	0.52	11.74	0.55	0.55	166.83
BOTA	900	119.56	42.89	0.35	8.50	0.48	0.55	172.32
BOTA	1200	144.50	51.67	0.26	7.38	0.58	0.55	204.94
BOTA	1500	144.50	41.33	0.21	5.90	0.46	0.55	192.96
BOTA	2200	166.49	35.09	0.14	4.76	0.35	0.55	207.39
BOTA	3000	181.25	30.73	0.10	4.65	0.34	0.55	217.63
BOTA	3700	225.83	32.00	0.08	4.40	0.33	0.55	263.19
BOTA	4500	255.16	29.87	0.07	3.96	0.30	0.55	289.92

UNIT FILLING COSTS

TECHNOLOGY	RATE	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	CONTAINER	TOTAL COSTS
PLBT	225	81.30	320.00	3.33	0.00	4.22	8.75	417.61
PLBT	450	121.31	226.67	1.67	0.00	3.89	8.75	362.28
PLBT	600	170.98	230.00	2.08	0.00	3.75	8.75	415.56
PLBT	900	217.72	188.89	1.67	0.00	3.33	8.75	420.36
PLBT	1200	242.77	166.67	1.25	0.00	3.12	8.75	422.56
PLBT	1500	277.73	166.67	1.17	0.00	2.83	8.75	457.15
PLBT	2200	318.38	168.18	0.91	0.00	2.27	8.75	498.50
PLBT	3000	374.42	152.00	0.75	0.00	2.10	8.75	538.02
PLBT	3700	409.21	156.22	0.68	0.00	1.82	8.75	576.68
PLBT	4500	420.94	155.56	0.61	0.00	1.58	8.75	587.43
CARM	225	27.80	88.00	1.11	0.05	0.12	13.95	131.03
CARM	450	37.50	52.00	1.11	0.11	0.09	13.95	104.76
CARM	600	56.16	44.33	0.83	0.18	0.07	13.95	115.53
CARM	900	66.82	50.00	0.83	0.22	0.07	13.95	131.90
CARM	1200	115.31	50.83	0.62	0.18	0.07	13.95	180.97
CARM	1500	133.64	74.13	1.00	0.24	0.06	13.95	223.03
CARM	2200	196.15	71.27	1.02	0.20	0.06	13.95	282.65
CARM	3000	258.30	63.47	1.00	0.24	0.06	13.95	337.01
CARM	3700	319.51	56.22	1.01	0.22	0.06	13.95	390.96
CARM	4500	363.88	60.00	1.00	0.20	0.06	13.95	439.08
CARA	225	54.00	105.78	1.11	0.05	0.09	13.95	174.97
CARA	450	70.44	60.89	0.56	0.11	0.09	13.95	146.04
CARA	600	113.82	57.67	0.42	0.18	0.07	13.95	186.10
CARA	900	146.13	57.33	0.28	0.18	0.07	13.95	217.94
CARA	1200	168.51	52.50	0.21	0.17	0.07	13.95	235.41
CARA	1500	189.85	52.00	0.17	0.17	0.07	13.95	256.21
CARA	2200	236.18	40.00	0.11	0.16	0.07	13.95	290.46
CARA	3000	275.69	32.67	0.08	0.13	0.06	13.95	322.59
CARA	3700	311.05	30.27	0.07	0.12	0.06	13.95	355.52
CARA	4500	341.74	28.89	0.06	0.11	0.05	13.95	384.79

D.P. FILLING COSTS, (H(S1,D1)

FILLING COSTS IN RELATION TO INPUTS FROM PASTEURIZATION STAGE

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10
BTH1	BOTM	234.62	204.10	249.46	254.50	267.57	293.50	474.71	521.15	601.16	867.27
BTH1	BOMA	290.04	227.49	268.60	267.23	280.03	296.86	467.93	515.13	587.82	846.21
BTH1	BOTA	340.86	250.27	321.12	322.30	354.92	342.94	507.34	517.58	563.15	805.95
BTH1	PLBT	572.96	483.10	569.85	570.34	572.54	607.13	798.45	837.98	876.63	1103.47
BTH1	CARM	286.39	225.59	269.81	281.88	330.95	373.01	582.61	636.97	690.92	955.12
BTH1	CARA	330.33	266.86	340.38	367.91	385.38	406.19	590.42	622.54	655.47	900.82
BTH2	BOTM	134.78	170.84	208.36	166.93	201.67	227.60	253.74	300.18	380.20	509.22
BTH2	BOMA	190.19	194.23	227.50	179.66	214.13	230.95	246.96	294.16	366.85	488.15
BTH2	BOTA	241.01	217.01	280.02	234.74	289.02	277.04	286.38	296.62	342.18	447.89
BTH2	PLBT	473.11	449.85	528.75	482.77	506.64	541.23	577.49	617.01	655.67	745.41
BTH2	CARM	186.54	192.33	228.71	194.31	265.05	307.11	361.64	416.00	469.95	597.06
BTH2	CARA	230.48	233.61	299.29	280.35	319.48	340.29	369.45	401.57	434.50	542.77
BTH3	BOTM	96.13	111.52	128.39	155.52	141.62	176.73	219.79	264.68	344.70	394.74
BTH3	BOMA	151.54	134.92	147.53	168.25	154.08	180.08	213.01	258.67	331.36	373.67
BTH3	BOTA	202.37	157.70	200.05	223.33	228.97	226.17	252.43	261.12	306.68	333.41
BTH3	PLBT	434.47	390.53	448.78	471.37	446.59	490.36	543.54	581.51	620.17	630.93
BTH3	CARM	147.89	133.02	148.75	182.91	205.00	256.24	327.69	380.51	434.46	482.58
BTH3	CARA	191.83	174.29	219.32	268.94	259.44	289.41	335.50	366.08	399.01	428.29
BTH4	BOTM	94.68	105.16	121.97	136.29	160.43	191.63	202.16	255.56	337.55	383.14
BTH4	BOMA	150.09	128.55	141.12	149.02	172.88	194.98	195.38	249.54	324.20	362.07
BTH4	BOTA	200.92	151.33	193.64	204.09	247.77	241.07	234.79	252.00	299.53	321.81
BTH4	PLBT	433.02	384.16	442.36	452.13	465.40	505.26	525.90	572.39	613.02	619.33
BTH4	CARM	146.44	126.65	142.33	163.67	223.80	271.14	310.06	371.38	427.30	470.98
BTH4	CARA	190.38	167.92	212.90	249.71	278.24	304.32	317.87	356.96	391.85	416.69
BTH5	BOTM	94.20	104.67	116.57	130.84	155.25	185.87	194.91	246.66	332.68	384.68
BTH5	BOMA	149.61	128.06	135.71	143.57	167.70	189.23	188.13	240.65	319.33	363.61
BTH5	BOTA	200.43	150.84	188.23	198.64	242.59	235.31	227.55	243.10	294.66	323.35
BTH5	PLBT	432.53	383.68	436.96	446.68	460.22	499.50	518.66	563.49	608.15	620.87
BTH5	CARM	145.96	126.16	136.93	158.22	218.62	265.38	302.81	362.48	422.44	472.52
BTH5	CARA	189.90	167.44	207.50	244.25	273.06	298.56	310.63	348.06	386.99	418.23

D.F. FILLING COSTS, (H(S1,D1)

FILLING COSTS IN RELATION TO INPUTS FROM PASTEURIZATION STAGE

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10
HTT1	BOTM	177.23	151.96	187.99	229.43	234.48	260.41	291.63	454.96	534.98	585.01
HTT1	BOMA	232.65	175.35	207.13	242.16	246.93	263.76	284.86	448.94	521.63	563.94
HTT1	BOTA	283.47	198.13	259.65	297.24	321.82	309.85	324.27	451.39	496.96	523.68
HTT1	PLBT	515.57	430.96	508.38	545.28	539.45	574.03	615.38	771.79	810.45	821.20
HTT1	CARM	229.00	173.45	208.34	256.81	297.85	339.91	399.53	570.78	624.73	672.85
HTT1	CARA	272.93	214.73	278.92	342.85	352.29	373.09	407.35	556.35	589.28	618.56
HTT2	BOTM	123.14	146.91	180.94	146.98	172.81	212.87	239.34	285.78	365.80	415.83
HTT2	BOMA	178.55	170.30	200.08	159.71	185.26	216.22	232.56	279.76	352.45	394.77
HTT2	BOTA	229.37	193.08	252.60	214.78	260.15	262.30	271.98	282.22	327.78	354.50
HTT2	PLBT	461.47	425.92	501.33	462.82	477.77	526.49	563.09	602.61	641.27	652.02
HTT2	CARM	174.90	168.40	201.29	174.36	236.18	292.37	347.24	401.60	455.55	503.67
HTT2	CARA	218.84	209.68	271.87	260.39	290.62	325.55	355.05	387.17	420.10	449.38
HTT3	BOTM	94.73	105.21	122.02	136.34	160.48	191.73	202.36	255.86	337.85	383.54
HTT3	BOMA	150.14	128.60	141.17	149.07	172.93	195.08	195.58	249.84	324.50	362.47
HTT3	BOTA	200.97	151.38	193.69	204.14	247.82	241.17	234.99	252.30	299.83	322.21
HTT3	PLBT	433.07	384.21	442.41	452.18	465.45	505.36	526.10	572.69	613.32	619.73
HTT3	CARM	146.49	126.70	142.38	163.72	223.85	271.24	310.26	371.68	427.60	471.38
HTT3	CARA	190.43	167.97	212.95	249.76	278.29	304.42	318.07	357.26	392.15	417.09
HTT4	BOTM	99.70	97.23	109.13	124.95	142.95	168.88	211.44	262.57	353.00	369.47
HTT4	BOMA	155.12	120.62	128.27	137.68	155.40	172.23	204.66	256.56	339.66	348.41
HTT4	BOTA	205.94	143.40	180.79	192.76	230.29	218.31	244.08	259.01	314.98	308.14
HTT4	PLBT	438.04	376.24	429.52	440.79	447.92	482.50	535.19	579.40	628.47	605.66
HTT4	CARM	151.47	118.72	129.48	152.33	206.32	248.38	319.34	378.40	442.76	457.31
HTT4	CARA	195.41	160.00	200.06	238.37	260.76	281.56	327.15	363.97	407.31	403.02
HTT5	BOTM	99.33	103.33	115.23	124.58	137.65	168.50	199.73	251.13	337.52	392.25
HTT5	BOMA	154.74	126.72	134.37	137.31	150.11	171.85	192.95	245.12	324.18	371.19
HTT5	BOTA	205.56	149.50	186.89	192.38	225.00	217.94	232.37	247.57	299.50	330.92
HTT5	PLBT	437.67	382.34	435.62	440.42	442.62	482.13	523.47	567.96	612.99	628.44
HTT5	CARM	151.09	124.82	135.58	151.96	201.03	248.01	307.63	366.96	427.28	480.09
HTT5	CARA	195.03	166.10	206.16	237.99	255.46	281.19	315.44	352.53	391.83	425.80

D.P. FILLING COSTS, (H(S1,D1)

FILLING COSTS IN RELATION TO INPUTS FROM PASTEURIZATION STAGE

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10
HTT6	BOTM	104.12	108.12	115.10	124.45	137.53	163.46	199.60	251.01	337.40	387.43
HTT6	BOMA	159.54	131.52	134.25	137.18	149.98	166.81	192.82	244.99	324.05	366.36
HTT6	BOTA	210.36	154.30	186.77	192.26	224.87	212.89	232.24	247.45	299.38	326.10
HTT6	PLBT	442.46	387.13	435.50	440.29	442.50	477.08	523.35	567.84	612.87	623.62
HTT6	CARM	155.89	129.62	135.46	151.83	200.90	242.96	307.50	366.83	427.15	475.27
HTT6	CARA	199.83	170.89	206.03	237.87	255.34	276.14	315.32	352.41	391.70	420.98
HTT7	BOTM	108.84	112.84	124.74	134.09	147.16	173.09	204.32	250.76	330.78	387.18
HTT7	BOMA	164.26	136.23	143.88	146.82	159.62	176.45	197.54	244.74	317.43	366.11
HTT7	BOTA	215.08	159.01	196.40	201.89	234.51	222.53	236.96	247.20	292.76	325.85
HTT7	PLBT	447.18	391.85	445.13	449.93	452.13	486.72	528.07	567.59	606.25	623.37
HTT7	CARM	160.60	134.33	145.10	161.47	210.54	252.60	312.22	366.58	420.53	475.02
HTT7	CARA	204.54	175.61	215.67	247.51	264.98	285.78	320.03	352.16	385.09	420.73
HTT8	BOTM	119.82	123.82	135.72	145.07	158.14	179.38	210.60	257.04	337.06	387.10
HTT8	BOMA	175.24	147.21	154.87	157.80	170.60	182.73	203.83	251.03	323.72	366.03
HTT8	BOTA	226.06	169.99	207.38	212.87	245.49	228.82	243.24	253.48	299.04	325.77
HTT8	PLBT	458.16	402.83	456.11	460.91	463.11	493.00	534.35	573.87	612.53	623.29
HTT8	CARM	171.59	145.31	156.08	172.45	221.52	258.89	318.51	372.87	426.82	474.94
HTT8	CARA	215.52	186.59	226.65	258.49	275.96	292.06	326.32	358.44	391.37	420.65
HTT9	BOTM	95.70	99.70	111.60	120.95	134.02	159.95	191.18	271.18	351.20	401.24
HTT9	BOMA	151.11	123.09	130.74	133.68	146.48	163.31	184.40	265.17	337.86	380.17
HTT9	BOTA	201.94	145.87	183.26	188.75	221.37	209.39	223.82	267.62	313.18	339.91
HTT9	PLBT	434.04	378.71	431.99	436.79	438.99	473.58	514.93	588.01	626.67	637.43
HTT9	CARM	147.46	121.19	131.95	148.33	197.40	239.46	299.08	387.01	440.96	489.08
HTT9	CARA	191.40	162.47	202.53	234.36	251.84	272.64	306.89	372.58	405.51	434.79
HT10	BOTM	99.32	103.32	115.22	124.56	137.64	163.57	194.80	241.24	321.25	371.29
HT10	BOMA	154.73	126.71	134.36	137.29	150.10	166.92	188.02	235.22	307.91	350.22
HT10	BOTA	205.55	149.49	186.88	192.37	224.98	213.01	227.43	237.67	283.24	309.96
HT10	PLBT	437.65	382.32	435.61	440.41	442.61	477.20	518.54	558.06	596.72	607.48
HT10	CARM	151.08	124.81	135.57	151.95	201.02	243.08	302.70	357.06	411.01	459.13
HT10	CARA	195.02	166.09	206.14	237.98	255.45	276.26	310.51	342.63	375.56	404.84

DYNAMIC PROGRAMMING RESULTS

2-STAGE COST DATA
G(S2,D2)

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10	MINIMUM
BTH1	BOTM	235.78	204.69	249.91	255.13	268.07	294.12	475.32	521.76	601.81	867.94	204.69
BTH1	BOMA	291.19	228.08	269.06	267.86	280.52	297.47	468.54	515.74	588.46	846.87	228.08
BTH1	BOTA	351.62	256.03	325.63	327.78	359.42	347.39	512.89	523.99	569.57	813.85	256.03
BTH1	PLBT	574.11	483.70	570.30	570.97	573.04	607.75	799.07	838.59	877.28	1104.13	483.70
BTH1	CARM	287.54	226.18	270.27	282.51	331.44	373.63	583.22	637.58	691.56	955.78	226.18
BTH1	CARA	341.09	272.62	344.89	373.39	389.89	410.64	595.97	628.95	661.89	908.73	272.62
BTH2	BOTM	135.93	171.44	208.81	167.56	202.17	228.22	254.35	300.79	380.84	509.89	135.93
BTH2	BOMA	191.34	194.83	227.96	180.29	214.62	231.57	247.57	294.78	367.49	488.82	180.29
BTH2	BOTA	251.77	222.77	284.53	240.21	293.52	281.49	291.92	303.02	348.60	455.80	222.77
BTH2	PLBT	474.26	450.44	529.21	483.41	507.14	541.85	578.10	617.62	656.31	746.08	450.44
BTH2	CARM	187.69	192.93	229.17	194.95	265.54	307.73	362.25	416.62	470.60	597.73	187.69
BTH2	CARA	241.24	239.37	303.79	285.83	323.99	344.74	375.00	407.98	440.93	550.68	239.37
BTH3	BOTM	97.28	112.12	128.85	156.16	142.12	177.35	220.40	265.30	345.35	395.40	97.28
BTH3	BOMA	152.70	135.51	147.99	168.89	154.57	180.70	213.62	259.28	332.00	374.34	135.51
BTH3	BOTA	213.12	163.45	204.56	228.81	233.47	230.62	257.97	267.52	313.11	341.32	163.45
BTH3	PLBT	435.62	391.13	449.24	472.00	447.09	490.97	544.15	582.13	620.81	631.59	391.13
BTH3	CARM	149.04	133.61	149.20	183.54	205.49	256.85	328.30	381.12	435.10	483.24	133.61
BTH3	CARA	202.59	180.05	223.83	274.42	263.94	293.86	341.05	372.48	405.43	436.19	180.05
BTH4	BOTM	95.83	105.75	122.43	136.92	160.92	192.25	202.77	256.18	338.19	383.80	95.83
BTH4	BOMA	151.25	129.14	141.57	149.65	173.38	195.60	195.99	250.16	324.84	362.74	129.14
BTH4	BOTA	211.67	157.09	198.14	209.57	252.28	245.52	240.34	258.40	305.95	329.72	157.09
BTH4	PLBT	434.17	384.76	442.82	452.77	465.89	505.87	526.52	573.00	613.66	620.00	384.76
BTH4	CARM	147.59	127.24	142.78	164.30	224.30	271.75	310.67	372.00	427.95	471.65	127.24
BTH4	CARA	201.14	173.68	217.41	255.18	282.75	308.76	323.42	363.36	398.28	424.59	173.68
BTH5	BOTM	95.35	105.27	117.03	131.47	155.74	186.49	195.52	247.28	333.32	385.35	95.35
BTH5	BOMA	150.76	128.66	136.17	144.20	168.20	189.85	188.75	241.26	319.98	364.28	128.66
BTH5	BOTA	211.19	156.60	192.74	204.12	247.10	239.76	233.10	249.50	301.08	331.26	156.60
BTH5	PLBT	433.68	384.27	437.42	447.31	460.71	500.12	519.27	564.11	608.79	621.54	384.27
BTH5	CARM	147.11	126.76	137.38	158.85	219.12	266.00	303.43	363.10	423.08	473.19	126.76
BTH5	CARA	200.66	173.20	212.01	249.73	277.57	303.01	316.17	354.46	393.41	426.14	173.20

2-STAGE COST DATA

G(S2,D2)

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10	MINIMUM
HTT1	BOTM	178.38	152.55	188.44	230.07	234.97	261.03	292.25	455.57	535.62	585.68	152.55
HTT1	BOMA	233.80	175.95	207.59	242.80	247.43	264.38	285.47	449.55	522.27	564.61	175.95
HTT1	BOTA	294.23	203.89	264.16	302.72	326.33	314.29	329.82	457.80	503.38	531.59	203.89
HTT1	PLBT	516.72	431.56	508.84	545.91	539.94	574.65	615.99	772.40	811.09	821.87	431.56
HTT1	CARM	230.15	174.05	208.80	257.45	298.35	340.53	400.15	571.39	625.37	673.52	174.05
HTT1	CARA	283.69	220.49	283.42	348.33	356.80	377.54	412.89	562.76	595.71	626.47	220.49
HTT2	BOTM	124.29	147.51	181.39	147.61	173.30	213.49	239.95	286.39	366.44	416.50	124.29
HTT2	BOMA	179.70	170.90	200.54	160.34	185.76	216.84	233.17	280.38	353.09	395.43	160.34
HTT2	BOTA	240.13	198.84	257.11	220.26	264.66	266.75	277.52	288.62	334.20	362.41	198.84
HTT2	PLBT	462.62	426.51	501.79	463.45	478.27	527.11	563.70	603.22	641.91	652.69	426.51
HTT2	CARM	176.05	169.00	201.75	174.99	236.68	292.99	347.85	402.22	456.20	504.34	169.00
HTT2	CARA	229.60	215.44	276.37	265.87	295.12	330.00	360.60	393.58	426.53	457.29	215.44
HTT3	BOTM	95.88	105.80	122.48	136.97	160.97	192.35	202.97	256.48	338.49	384.20	95.88
HTT3	BOMA	151.30	129.19	141.62	149.70	173.43	195.70	196.19	250.46	325.14	363.14	129.19
HTT3	BOTA	211.72	157.14	198.19	209.62	252.33	245.62	240.54	258.70	306.25	330.12	157.14
HTT3	PLBT	434.22	384.81	442.87	452.82	465.94	505.97	526.72	573.30	613.96	620.40	384.81
HTT3	CARM	147.64	127.29	142.83	164.35	224.35	271.85	310.87	372.30	428.25	472.04	127.29
HTT3	CARA	201.19	173.73	217.46	255.23	282.80	308.86	323.62	363.66	398.58	424.99	173.73
HTT4	BOTM	100.86	97.83	109.59	125.59	143.44	169.49	212.05	263.19	353.64	370.14	97.83
HTT4	BOMA	156.27	121.22	128.73	138.32	155.90	172.85	205.27	257.17	340.30	349.07	121.22
HTT4	BOTA	216.70	149.16	185.30	198.24	234.80	222.76	249.62	265.41	321.41	316.05	149.16
HTT4	PLBT	439.19	376.83	429.98	441.43	448.41	483.12	535.80	580.02	629.11	606.33	376.83
HTT4	CARM	152.62	119.32	129.94	152.97	206.82	249.00	319.95	379.01	443.40	457.98	119.32
HTT4	CARA	206.17	165.76	204.57	243.85	265.26	286.01	332.70	370.37	413.73	410.93	165.76
HTT5	BOTM	100.48	103.93	115.68	125.21	138.15	169.12	200.34	251.75	338.16	392.92	100.48
HTT5	BOMA	155.89	127.32	134.83	137.94	150.60	172.47	193.56	245.73	324.82	371.85	127.32
HTT5	BOTA	216.32	155.26	191.40	197.86	229.50	222.39	237.91	253.97	305.93	338.83	155.26
HTT5	PLBT	438.82	382.93	436.08	441.05	443.12	482.75	524.09	568.58	613.63	629.11	382.93
HTT5	CARM	152.24	125.42	136.04	152.59	201.52	248.63	308.24	367.57	427.92	480.76	125.42
HTT5	CARA	205.79	171.86	210.67	243.47	259.97	285.64	320.99	358.93	398.25	433.71	171.86

2-STAGE COST DATA
G(S2,D2)

PAST.TECH	FILLER	RATE1	RATE2	RATE3	RATE4	RATE5	RATE6	RATE7	RATE8	RATE9	RATE10	MINIMUM
HTT6	BOTM	105.27	108.72	115.56	125.09	138.02	164.08	200.21	251.62	338.04	388.10	105.27
HTT6	BOMA	160.69	132.11	134.70	137.82	150.48	167.43	193.44	245.61	324.69	367.03	132.11
HTT6	BOTA	221.12	160.05	191.27	197.74	229.38	217.34	237.79	253.85	305.80	334.01	160.05
HTT6	PLBT	443.61	387.73	435.95	440.93	442.99	477.70	523.96	568.45	613.51	624.29	387.73
HTT6	CARM	157.04	130.21	135.92	152.47	201.40	243.58	308.12	367.45	427.80	475.94	130.21
HTT6	CARA	210.58	176.65	210.54	243.35	259.85	280.59	320.86	358.81	398.13	428.89	176.65
HTT7	BOTM	109.99	113.44	125.20	134.72	147.66	173.71	204.93	251.37	331.42	387.85	109.99
HTT7	BOMA	165.41	136.83	144.34	147.45	160.12	177.07	198.16	245.36	318.08	366.78	136.83
HTT7	BOTA	225.84	164.77	200.91	207.37	239.02	226.98	242.51	253.60	299.18	333.76	164.77
HTT7	PLBT	448.33	392.44	445.59	450.57	452.63	487.34	528.68	568.20	606.89	624.04	392.44
HTT7	CARM	161.76	134.93	145.55	162.10	211.03	253.22	312.83	367.20	421.18	475.69	134.93
HTT7	CARA	215.30	181.37	220.18	252.98	269.48	290.23	325.58	358.56	391.51	428.64	181.37
HTT8	BOTM	120.97	124.42	136.18	145.70	158.64	180.00	211.22	257.66	337.71	387.76	120.97
HTT8	BOMA	176.39	147.81	155.32	158.43	171.10	183.35	204.44	251.64	324.36	366.70	147.81
HTT8	BOTA	236.82	175.75	211.89	218.35	250.00	233.27	248.79	259.88	305.47	333.68	175.75
HTT8	PLBT	459.31	403.42	456.57	461.55	463.61	493.62	534.97	574.49	613.18	623.96	403.42
HTT8	CARM	172.74	145.91	156.53	173.08	222.02	259.50	319.12	373.48	427.46	475.61	145.91
HTT8	CARA	226.28	192.35	231.16	263.96	280.46	296.51	331.87	364.84	397.79	428.55	192.35
HTT9	BOTM	96.85	100.30	112.06	121.58	134.52	160.57	191.79	271.80	351.84	401.90	96.85
HTT9	BOMA	152.27	123.69	131.20	134.31	146.97	163.93	185.01	265.78	338.50	380.84	123.69
HTT9	BOTA	212.69	151.63	187.77	194.23	225.87	213.84	229.36	274.02	319.61	347.81	151.63
HTT9	PLBT	435.19	379.30	432.45	437.42	439.49	474.20	515.54	588.63	627.31	638.09	379.30
HTT9	CARM	148.61	121.79	132.41	148.96	197.89	240.08	299.69	387.62	441.60	489.74	121.79
HTT9	CARA	202.16	168.23	207.04	239.84	256.34	277.09	312.44	378.98	411.93	442.69	168.23
HT10	BOTM	100.47	103.91	115.67	125.20	138.14	164.19	195.41	241.85	321.90	371.95	100.47
HT10	BOMA	155.88	127.31	134.82	137.93	150.59	167.54	188.63	235.83	308.55	350.89	127.31
HT10	BOTA	216.31	155.25	191.39	197.85	229.49	217.46	232.98	244.08	289.66	317.87	155.25
HT10	PLBT	438.80	382.92	436.06	441.04	443.10	477.81	519.16	558.68	597.37	608.15	382.92
HT10	CARM	152.23	125.40	136.03	152.58	201.51	243.70	303.31	357.67	411.65	459.80	125.40
HT10	CARA	205.78	171.84	210.65	243.46	259.96	280.70	316.06	349.03	381.98	412.74	171.84

OPTIMAL VALUES FOR STAGE 2

PAST. TECH	FILLING TECH	OPTIMUM
BTH1	BOTH	204.69
BTH2	BOTH	135.93
BTH3	BOTH	97.28
BTH4	BOTH	95.83
BTH5	BOTH	95.35
HTT1	BOTH	152.55
HTT2	BOTH	124.29
HTT3	BOTH	95.88
HTT4	BOTH	97.83
HTT5	BOTH	100.48
HTT6	BOTH	105.27
HTT7	BOTH	109.99
HTT8	BOTH	120.97
HTT9	BOTH	96.85
HT10	BOTH	100.47

THIS IS THE BEGINNING OF STAGE 3 - PASTEURIZATION

UNIT PASTEURIZATION COSTS

TECHNOLOGY	CAPITAL	LABOUR	ELECTRICITY	FUEL	TOTAL PAST. COSTS
BTH1	30.70	12.60	166.32	11.61	221.22
BTH2	15.39	6.80	89.76	12.36	124.31
BTH3	8.28	3.90	51.48	14.18	77.84
BTH4	8.93	2.45	32.34	17.82	61.53
BTH5	10.14	1.97	25.96	21.45	59.52
HTT1	30.84	2.50	88.00	0.44	121.78
HTT2	21.19	1.25	44.00	0.63	67.07
HTT3	17.29	0.62	45.00	0.78	63.69
HTT4	18.36	0.25	18.00	2.04	38.64
HTT5	19.17	0.16	11.25	2.55	33.12
HTT6	28.48	0.12	25.00	4.07	57.68
HTT7	44.86	0.06	15.20	8.06	68.18
HTT8	46.25	0.04	10.13	12.22	68.64
HTT9	49.58	0.02	7.36	20.34	77.30
HT10	55.69	0.02	5.15	32.53	93.38

D.P. PASTEURIZATION COSTS (H(S3,D3))

PASTEURIZATION COSTS IN RELATION TO INPUT RATES FROM RECEPTION STAGE

INPUT RATE	BATCH1	BATCH2	BATCH3	BATCH4	BATCH5	HTST1	HTST2	HTST3	HTST4	HTST5	HTST6	HTST7	HTST8	HTST9	HTST10
1000	258.67	155.97	106.59	88.83	86.34	156.63	96.92	91.04	59.57	53.68	78.11	93.28	98.62	118.29	110.73
2000	263.39	160.68	111.31	93.55	91.06	161.35	101.64	95.76	69.21	63.32	87.75	93.03	98.37	113.34	134.08
3000	274.37	171.66	122.29	104.53	102.04	172.33	112.62	106.74	80.19	74.30	98.73	104.29	104.66	117.95	137.04
4000	289.88	181.37	129.10	109.89	106.91	185.24	120.53	112.14	84.10	77.83	102.14	112.14	112.43	120.96	136.96
5000	262.85	154.34	102.07	82.86	79.88	158.21	93.50	85.11	57.07	50.80	75.11	85.11	118.96	127.50	109.93
6000	262.82	154.31	102.04	82.83	79.85	158.18	93.47	85.08	57.04	50.77	75.08	85.08	85.37	93.90	109.90
7000	289.51	169.41	111.33	89.22	85.28	179.67	104.96	91.58	60.53	53.52	77.57	87.07	87.19	95.59	111.52
8000	316.87	185.16	121.29	96.28	91.37	201.83	117.12	98.73	64.69	56.92	80.73	89.73	89.68	97.95	111.49
9000	316.83	185.12	121.24	96.24	91.32	201.79	117.08	98.69	64.65	56.88	80.69	89.69	89.64	97.91	113.76
10000	318.76	187.05	123.18	98.17	93.26	203.72	119.01	100.62	66.58	58.81	82.62	91.62	91.58	99.84	115.69

DYNAMIC PROGRAMMING RESULTS

3-STAGE COST DATA
G(S3,D3)

RECEPTION RATE	BATCH1	BATCH2	BATCH3	BATCH4	BATCH5	HTST1	HTST2	HTST3	HTST4	HTST5	HTST6	HTST7	HTST8	HTST9	HTST10	MINIMUM
1000	463.36	291.89	203.87	184.67	181.69	309.19	221.21	186.92	157.40	154.16	183.39	203.28	219.60	215.14	211.20	154.16
2000	468.08	296.61	208.59	189.38	186.40	313.91	225.93	191.64	167.04	163.80	193.03	203.03	219.35	210.19	234.55	163.80
3000	479.06	307.59	219.57	200.36	197.38	324.89	236.91	202.62	178.02	174.78	204.01	214.28	225.63	214.80	237.51	174.78
4000	494.57	317.30	226.38	205.72	202.26	337.79	244.82	208.02	181.92	178.31	207.41	222.13	233.40	217.81	237.43	178.31
5000	467.54	290.27	199.35	178.69	175.23	310.76	217.79	181.00	154.90	151.28	180.38	195.10	239.94	224.35	210.40	151.28
6000	467.51	290.24	199.32	178.66	175.20	310.73	217.76	180.96	154.86	151.25	180.35	195.07	206.34	190.75	210.37	151.25
7000	494.20	305.33	208.61	185.05	180.63	332.23	229.25	187.46	158.36	154.00	182.85	197.07	208.17	192.45	211.99	154.00
8000	521.56	321.09	218.57	192.11	186.71	354.38	241.41	194.61	162.51	157.40	186.00	199.72	210.66	194.80	211.95	157.40
9000	521.52	321.05	218.53	192.07	186.67	354.34	241.37	194.57	162.47	157.36	185.96	199.68	210.61	194.76	214.23	157.36
10000	523.45	322.98	220.46	194.00	188.61	356.27	243.30	196.51	164.41	159.29	187.89	201.61	212.55	196.69	216.16	159.29

THIS IS THE BEGINNING OF STAGE 4 - RECEPTION

UNIT RECEPTION COSTS

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN1	1000	53.58	0.00	1.52	1.51	0.04	56.65
CAN1	2000	107.13	0.00	1.52	1.51	0.04	110.20
CAN1	3000	111.39	0.00	1.27	1.51	0.04	114.21
CAN1	4000	164.94	0.00	1.33	1.51	0.04	167.82
CAN1	5000	218.64	0.00	1.37	1.51	0.04	221.56
CAN1	6000	222.74	0.00	1.27	1.51	0.04	225.56
CAN1	7000	276.29	0.00	1.31	1.51	0.04	279.14
CAN1	8000	330.14	0.00	1.33	1.51	0.04	333.03
CAN1	9000	334.40	0.00	1.27	1.51	0.04	337.22
CAN1	10000	373.26	0.00	1.29	1.51	0.04	376.11
CAN2	1000	56.39	1.80	1.02	4.23	0.10	63.54
CAN2	2000	112.78	1.80	1.02	4.23	0.10	119.94
CAN2	3000	115.66	1.20	0.69	2.82	0.07	120.43
CAN2	4000	172.05	1.35	0.77	3.18	0.07	177.42
CAN2	5000	228.44	1.44	0.82	3.39	0.08	234.16
CAN2	6000	231.31	1.20	0.69	2.82	0.07	236.09
CAN2	7000	287.70	1.29	0.73	3.02	0.07	292.82
CAN2	8000	344.09	1.35	0.77	3.18	0.07	349.46
CAN2	9000	346.97	1.20	0.69	2.82	0.07	351.75
CAN2	10000	388.98	1.26	0.72	2.96	0.07	393.99

UNIT RECEPTION COSTS

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
CAN3	1000	77.17	39.60	0.63	4.84	0.13	122.38
CAN3	2000	77.17	19.80	0.32	2.42	0.07	99.78
CAN3	3000	79.17	13.87	0.22	2.02	0.05	95.33
CAN3	4000	82.29	10.40	0.17	1.66	0.04	94.55
CAN3	5000	107.83	13.64	0.16	2.18	0.06	123.86
CAN3	6000	109.83	11.70	0.13	2.02	0.05	123.73
CAN3	7000	116.05	10.03	0.12	1.99	0.04	128.23
CAN3	8000	123.88	10.10	0.12	2.12	0.05	136.27
CAN3	9000	127.61	9.20	0.11	2.02	0.05	138.98
CAN3	10000	150.55	11.00	0.15	2.00	0.05	163.74
CAN4	1000	88.70	39.60	0.63	4.84	0.13	133.91
CAN4	2000	88.70	19.80	0.32	2.42	0.07	111.31
CAN4	3000	90.70	13.87	0.22	2.02	0.05	106.86
CAN4	4000	101.21	12.55	0.17	1.66	0.07	115.66
CAN4	5000	113.21	13.64	0.11	2.18	0.06	129.19
CAN4	6000	115.21	11.70	0.09	2.02	0.05	129.07
CAN4	7000	121.43	10.03	0.08	1.99	0.04	133.58
CAN4	8000	129.26	10.10	0.09	2.12	0.05	141.62
CAN4	9000	131.26	9.20	0.08	2.02	0.05	142.61
CAN4	10000	134.41	9.54	0.07	2.00	0.05	146.07

UNIT RECEPTION COSTS

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK1	1000	5.96	4.40	0.31	1.51	0.02	12.21
TNK1	2000	6.24	2.60	0.19	1.51	0.01	10.55
TNK1	3000	6.27	2.07	0.15	1.51	0.01	10.01
TNK1	4000	6.46	1.90	0.13	1.51	0.01	10.00
TNK1	5000	6.65	1.64	0.16	1.51	0.00	9.97
TNK1	6000	6.66	1.43	0.15	1.51	0.00	9.76
TNK1	7000	6.68	1.31	0.14	1.51	0.00	9.64
TNK1	8000	6.71	1.20	0.13	1.51	0.00	9.56
TNK1	9000	6.92	1.09	0.12	1.51	0.00	9.65
TNK1	10000	6.94	1.06	0.11	1.51	0.00	9.63
TNK2	1000	27.08	5.40	0.30	1.51	0.02	34.32
TNK2	2000	27.50	3.10	0.18	1.51	0.01	32.30
TNK2	3000	27.55	2.40	0.14	1.51	0.01	31.61
TNK2	4000	27.82	2.15	0.12	1.51	0.01	31.61
TNK2	5000	28.11	1.84	0.15	1.51	0.00	31.62
TNK2	6000	28.13	1.60	0.14	1.51	0.00	31.38
TNK2	7000	28.15	1.46	0.13	1.51	0.00	31.25
TNK2	8000	28.20	1.32	0.12	1.51	0.00	31.16
TNK2	9000	28.51	1.20	0.11	1.51	0.00	31.34
TNK2	10000	28.53	1.16	0.10	1.51	0.00	31.31

UNIT RECEPTION COSTS

TECHNOLOGY	RATE PER HOUR	CAPITAL	ELECTRICITY	LABOUR	FUEL	WATER	RECEPTION COSTS
TNK3	1000	11.62	4.60	0.30	1.51	0.02	18.06
TNK3	2000	11.91	2.70	0.18	1.51	0.01	16.31
TNK3	3000	12.14	2.13	0.14	1.51	0.01	15.93
TNK3	4000	12.45	1.95	0.12	1.51	0.01	16.04
TNK3	5000	12.58	1.64	0.15	1.51	0.00	15.89
TNK3	6000	12.66	1.47	0.14	1.51	0.00	15.78
TNK3	7000	12.87	1.34	0.13	1.51	0.00	15.86
TNK3	8000	13.11	1.20	0.12	1.51	0.00	15.94
TNK3	9000	13.26	1.11	0.11	1.51	0.00	15.99
TNK3	10000	13.27	1.08	0.10	1.51	0.00	15.97
TNK4	1000	29.62	4.80	0.56	1.51	0.02	36.52
TNK4	2000	29.90	2.70	0.31	1.51	0.01	34.44
TNK4	3000	29.93	2.20	0.23	1.51	0.01	33.88
TNK4	4000	30.11	2.05	0.19	1.51	0.01	33.87
TNK4	5000	30.31	1.76	0.21	1.51	0.00	33.80
TNK4	6000	30.32	1.57	0.19	1.51	0.00	33.60
TNK4	7000	30.34	1.43	0.17	1.51	0.00	33.45
TNK4	8000	30.37	1.30	0.16	1.51	0.00	33.35
TNK4	9000	30.58	1.20	0.15	1.51	0.00	33.45
TNK4	10000	30.60	1.12	0.14	1.51	0.00	33.37

D.P. RECEPTION COSTS (H(S1,D1))

RECEPTION COSTS IN RELATION TO INPUT STATES

TECHNOLOGY	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
CAN1	56.65	110.20	114.21	167.82	221.56	225.56	279.14	333.03	337.22	376.11
CAN2	63.54	119.94	120.43	177.42	234.16	236.09	292.82	349.46	351.75	393.99
CAN3	122.38	99.78	95.33	94.55	123.86	123.73	128.23	136.27	138.98	163.74
CAN4	133.91	111.31	106.86	115.66	129.19	129.07	133.58	141.62	142.61	146.07
TNK1	12.21	10.55	10.01	10.00	9.97	9.76	9.64	9.56	9.65	9.63
TNK2	34.32	32.30	31.61	31.61	31.62	31.38	31.25	31.16	31.34	31.31
TNK3	18.06	16.31	15.93	16.04	15.89	15.78	15.86	15.94	15.99	15.97
TNK4	36.52	34.44	33.88	33.87	33.80	33.60	33.45	33.35	33.45	33.37

DYNAMIC PROGRAMMING RESULTS

4-STAGE COST DATA
G(S4,D4)

TECHNOLOGY	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	MINIMUM
CAN1	210.82	274.00	288.99	346.13	372.84	376.81	433.14	490.43	494.58	535.40	210.82
CAN2	217.71	283.73	295.21	355.73	385.45	387.34	446.81	506.86	509.10	553.29	217.71
CAN3	276.54	263.58	270.11	272.87	275.14	274.98	282.23	293.67	296.34	323.04	263.58
CAN4	288.07	275.11	281.64	293.97	280.47	280.32	287.57	299.02	299.97	305.36	275.11
TNK1	166.37	174.35	184.79	188.31	161.26	161.01	163.64	166.96	167.01	168.92	161.01
TNK2	188.49	196.10	206.39	209.92	182.90	182.63	185.24	188.56	188.70	190.61	182.63
TNK3	172.23	180.11	190.71	194.35	167.18	167.03	169.86	173.35	173.35	175.26	167.03
TNK4	190.68	198.24	208.66	212.18	185.08	184.85	187.45	190.75	190.80	192.66	184.85

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THIS IS THE OVERALL LOWEST UNIT COST OF PRODUCTION

   CAN RECEPTION            TANKER RECEPTION


     210.82                   161.01
Command:
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APPENDIX 7.2

PROFIT MAXIMIZATION AND DYNAMIC PROGRAMMING IN A CHEMICAL PROCESS PLANT - AN ILLUSTRATION

The problem described here for illustrative purposes, is the familiar, often cited chemical process optimization problem attributed to Mitten and Nemhauser (1963). The sequential, acyclic, non-stationary process structure is similar to the dairy processing problem described in this thesis. The example has been chosen to illustrate the wider application of the D.P. technique by extending it to the profit maximization case and involving different control variables (temperature, efficiency, etc.). It is a smaller, more easily handled problem, with fewer components in the state and decision vectors than the problem worked in this thesis, and is useful for other applications of D.P. in the food processing industry as a whole.

The information on states, stages, decisions, transitions and the return function, and the data on costs provided in the tables have all been obtained from the version of the problem by Peters and Timmerhaus[1]. All the basic data were taken by the author of this thesis and used as the input to a computer programme coded in Fortran, designed to carry out the optimization procedure. The final tables from the staged optimization procedure are included with this appendix.

The product flows through five identifiable decision

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1 Peters & Timmerhaus (1969, pp. 733-741.

points (stages) from upstream to downstream. These are:

Mixing → Heating → 1st Reaction → 2nd Reaction → Separation.

The recursive optimization procedure is done in a direction which is the reverse of the product flow. The objective is to maximize profits and the decisions are taken with regard to mixing efficiency; temperature, first reaction conversion level and choice of catalyst; total reaction conversion and choice of separator. These are explained as the problem is worked through. The stages are dealt with separately from the final stage (in the plant).

i) Computation of Maximum 1 - Stage Profits

At stage 1 the total revenue is computed in relation to the quantity of output which results from the conversion rate of the reactors (the input state at stage 1).

Table I relates the expected selling price to the annual quantity of output.

TABLE I

Anticipated Selling Price of the Product vs. Annual Production

Production lbs '000/yr	Anticipated Selling price £/lb.
47.5	3.2
45.0	3.3
42.5	3.4
40.0	3.6
37.5	3.8
30.0	4.6
25.0	5.0
22.5	5.2
20.0	5.3
15.0	5.5

Since profits equal Revenue minus costs ($\pi = R - C$), the remainder of the exercise involves, subtracting costs from the revenue values determined at stage 1.

At this stage ($n = 1$), there are 10 conversion rates of the stream entering this separation stage from the second reaction stage. Thus for the input state vector S_1, $r = 1, \ldots, 10$. The actual output quantities are determined by the total conversion rate at the end of the two reaction stages (in time), based in this case, on an input volume of 50,000 lbs.

The decision, at this stage, D_1, is whether to use one large, or two small separators. Thus $m = 2$. The decision is made with regard to each conversion rate.

The optimal values of the profit function at this stage $f_n = g(S_n, D_h)$ can be found with knowledge of: the selling price in relation to the input conversion rates, and the initial and operating costs of the two separator alternatives as they vary with the state of the input. This information is found in Table II.

At stage 1 $g(S_1, D_1 = h(S\ , D\ )$. The one-stage profit over 5 years is:

5 year profit = 5-year revenue with respect to conversion rate minus 5-year separator costs relevant to that rate. That is:

5 year profit = [(input volume) × (conversion rate) × (expected selling price for that rate × no. of years of operation)] - [initial cost for separator for that rate) + (operating cost for that rate) × (no. of years of operation)]

TABLE II

Selling prices and Separation costs

Conversion Rate of Input %	'Expected' unit selling price of output £/lb.	One large Separator		Two small Separators cost per separator	
		Initial cost £1,000	Operating cost £1,000	Initial cost £1,000	Operating cost £1,000
30	5.5	12	2.5	7.5	1.5
40	5.3	12	3.0	7.5	1.5
45	5.2	12	4.0	7.5	1.5
50	5.0	15	4.0	9.0	1.5
60	4.6	15	5.0	9.0	2.0
75	3.8	20	6.0	12.0	2.0
80	3.6	20	6.5	12.0	2.0
85	3.4	20	7.0	12.0	2.0
90	3.3	20	7.5	12.0	2.5
95	3.2	20	8.0	12.0	2.5

Thus, for a conversion rate of 50%, given an initial input volume of 50,000 lbs.

A. the profit for one large separator is

$$[(50{,}000)(0.5)(£5.00)(5)] - [15{,}000 + (4{,}000)(5)]$$

$$= £625{,}000 - 35{,}000$$

$$= £590{,}000$$

and

B. the profit for two small separators is

$$[(50{,}000)(0.5)(£5.00)(5)] - 2[9{,}000 + (1{,}500)(5)]$$

$$= £625{,}000 - 33{,}000$$

$$= £592{,}000$$

indicating that at a 50% conversion rate ($r = 4$) maximum profit is obtained using two small separators ($m = 2$). This information is stored to be used at the backtracking stage.

Thus profit is evaluated for each input conversion rate/ separator combination, computing $h(S_1 = r, D_1 = m)$ for $r = 1, \ldots, 10$ for all $m = 1,2$ and noting that $g(S_1 = r, D_1 = m) = h(S_n = r, D_n = m)$ $f_1 = \max g_1$, is then found by a search over D_1 for each r.

These values have all been computed and are listed as tables at the end of this appendix.

ii) <u>Computation of Maximum 2 - Stage Profits</u>

This is the second sub-optimization. The relevant input variable S_2 is the conversion rate from the first reaction process, and there are 8 such input rates ($r = 1, \ldots, 8$). The decision is the type of second reactor to be used, and there are three choices (m = 1,2,3).

At this point a thorough knowledge of the technological relationship within reactor systems is required to relate conversion rates at the first reaction stage to those at the second reaction stage, so that the transformation relationship may be identified.

This technological information is presented in Table III.

TABLE III

Total Conversion out of Reactor II for Conversion in Reactor 1

Conversion in Reactor I	Total Conversion out of Reactor II: Reactor IIA	Reactor IIB
15	30	45
20	40	60
25	50	75
30	60	85
40	80	90
45	85	95
50	90	95
60	95	95

Table III reveals, for example, that if the input conversion rate from reactor I is 30%, then the decision to use reactor IIA transforms the input (at S_2) state of 30% conversion to an output state of 60% conversion, which is the input to stage 1 (S_1). A choice of reactor IIB would result in an output state of 85% conversion. There is also a choice of "no second reactor" and so the output conversion rate, when this decision is made, is identical to the input conversion rate.

It may be noted that constraints are imposed on the state variables. The total output from reactor II (the stage one input state vector) is limited to a minimum of 30% with the upper bound of 95% being limited by technological considerations. With the lower bound in force for stage 1, the choice of "no reactor II" cannot be entertained at stage 2, for input reaction conversions from reactor I below 30%. This is taken into account in the computations.

The computational procedure at this stage is as follows:

A. <u>The matching of the reactor conversion rates</u>

At stage 1 the profit was computed in relation to the total conversion rates out of reactor II (S_1) and so the 1-stage maximum values $f_1(S_1)$ were found in relation to these input rates. It is these values which must now be used in the 2-stage sub-optimization to find $f_2(S_2)$ where

$$f_2(S_2) = \max_{D2} g\left[h(S_2, D_2) \circ f_1(S_1)\right]$$

where o is the operator.

Using the data in Table III (above) for matching the rates, the appropriate f_1 values can be found to be used in the recursive procedure.

B. <u>Computation of the 2-stage return function $g(S_n, D_n)$ for $n = 2$.</u>

With n uncremented to n+1 = 2, and with 8 components of the input state variable S_2 (r = 1,..., 9) and three components of the decision variable D_2 (m = 1, ..., 3), the cumulative 2-stage return function is sought for all r and m.

For this particular type of problem the individual stage returns for any stage after stage 1, are only cost values. Thus $h(S_n, D_n)$ for n = 2,..., 5, is a penalty rather than a return and must carry a negative value.

The initial and operating costs (over a 5-year period) associated with the two reactors IIA and IIB, which represent the first two components of the decision variable D_2, are given, and no cost is associated with third decision component (m = 3).

Thus to obtain the array with values $g_2(S_2, D_2)$, the negative value of costs for every m (m = 1,2,3) is added algebraically to $f_1(S_1)$ (using the table matching the conversion rates) for every r (r = 1, ..., 8).

C. Determination of Maximum 2-stage Profits $f_2(S_2)$

This is obtained from the relationship $f_2(S_2) =$ $= \max g(S_n, D_n)$. It is essentially a search procedure to find the maximum value over D_2 for each input conversion level at stage 2 (m = 1, ..., 8) (see tabular section at back).

iii) Computation of Maximum 3-stage Profits

At stage 3, the input state vector contains the temperatures of the product coming in from the heating stage (stage 4). Four temperature values are used, and so at this stage r = 1, ..., 4.

There are two decision variables: type of reactor I (IA, IB or IC); and type of catalyst (type 1 or type 2). Thus, there are in all 3 × 2 decisions to consider. This extra dimension at this stage is not particularly troublesome since the components of each of the two decision vectors are few and the extra dimension does not have to be carried on to any other stage. Thus at this stage there are $4 \times 6 = 24$ computations to be made to find $h(S_2,D_2)$.

The transition relationship between stage 3 and stage 2 $S_2 = T_{D_3}(S_3)$, is derived from the relationship between the input temperatures and the decisions on catalyst and reactor I, and the percent conversion that is achieved in the first reactor. These are the input conversion rates for stage 2.

This information is provided in Table IV.

TABLE IV

Percent Conversion in Reactor 1

Input temperature %F	Reactor IA C_1	C^*_2	Reactor IB C^*_1	C^*_2	Reactor IC C^*_1	C^*_2
650	30	25	25	20	20	15
700	40	30	30	25	15	20
750	50	45	45	40	40	30
800	60	50	50	45	45	40

$^*C$ = catalyst.

The table indicates that, for example, if the incoming temperature is 700^oF (S_3 $(r = 2)$), the decision to use Reactor IA with catalyst 1 would result in an output conversion rate of 40% and hence in the recursive procedure, the appropriate maximum profit value $f_2(S_2)$ from which these costs must be subtracted would be that associated with the input state at stage 2 with a rate of 40%.

The cost data used for computing $h(S_3,D_3)$ is obtained from Table V below.

TABLE V

Costs of Reactors and Catalyst

	Initial cost £1,000	Operating cost £1,000/yr
Reactor 1A	40.0	4.0
Reactor 1B	20.0	2.0
Reactor 1C	5.0	1.0
Catalyst 1	----	10.0
Catalyst 2	----	4.0

The computational procedure is basically the same as for the previous stage:

A. Determination of the transition relationship and matching of the temperature (S_3), Reactor I and catalyst (D_2) to the conversion rate state of the product entering stage 2.

B. Computation of $h(S_3, D_3)$ for each incoming temperature and finding $g(S_3, D_3)$. This gives the three-stage profit for all combinations of temperature and reactors with the respective catalysts. Thus with $r = 1, \ldots, 4$ and $m = 6$, the twenty values are computed using the costs provided in Table V (to get $h(S_3, D_3)$ and the relevant maximum values from stage 2 ($f_2(S_2)$), matched by use of the data in Table IV. Thus three-stage profit for each r and m combination at stage 3 is (for one such combination):

$g(S_3, D_3)$ = [maximum profit for relevant % conversion at stage 2] - [(initial cost of reactor I) + (operating cost of reactor I for 5 years) + (operating cost of catalyst for 5 years)].

Using this formula, the 3 stage profits using reactor 1A, with catalyst 1 with an input temperature of 800°F, would be:

$= £542{,}000 \; [(40{,}000) + (4{,}000)5 + (10{,}000)(5)]$

$= £432{,}000.$

C. Determination of maximum 3-stage profit ($f_3(S_3)$).

This, again, is simply a search over all m decisions for each input temperature to find the maximum value with respect to each input temperature. The result of these computations indicate, for example, that, with an incoming temperature into the first reaction stage of 750°F, the optional choice would be reactor 1A with catalyst 1, thereby obtaining a maximum three stage profit of £516,000. The actual optimal input state would not be known until the back-tracking procedure is being carried out and the optimal policy is being contracted forwards in time from stage N to stage 1.

The results of the 3 stage maximum profits computation are presented in the tables at the end.

iv) Computation of the maximum 4-stage profits

The input states are described in terms of the mixing efficiency from stage 5, the mixing stage. Four mixing efficiencies are considered, therefore r = 1, ..., 4 at this stage. The relevant decision variable at this heating stage is temperature, with 4 component values (m = 1, ..., 4). Thus 4 × 4 = 16 calculations are required at this stage.

The transformation relationship in this case is very simple in that the input state to stage 3 (S_3) are simply the decisions at this stage (S_4). This relationship may be expressed as $S_3 = D_4$. It is therefore quite easy to find the maximum values from stage 3 $f_3(S_3)$ to be used in computing $g(S_4,D_4)$.

In order to compute the $h(S_4,D_4)$ the data in Table VI, relating costs to the combinations of input states and decisions on temperature is used.

TABLE VI

Heater Costs (£1,000/yr.)

Mixing Efficiency	Temperature $^{\circ}F$ 650		700		750		800	
	IC*	OC*	IC*	OC+	IC*	OC+	IC*	OC+
1.0	5	0.5	5	1.0	20	6.0	20	10.0
0.8	5	1.0	5	1.5	20	8.0	20	12.0
0.6	5	1.5	5	2.5	20	10.0	20	16.0
0.5	5	2.0	5	3.0	20	12.0	20	20.0

*Initial costs - These costs were not given explicitly by Peters & Timmerhaus but have been deduced.

\+ Operating costs.

Computation of the 4-stage profits with respect to mixing efficiency (S_4) follows much the same pattern as before. Thus, for example, to find $g(S_4,D_4)$, for a mixing efficiency of 0.8 and a temperature of 800°F, the computation would be:

= [Maximum 3-stage profit for $800^{\circ}F$] - [(Initial cost of heater for $800^{\circ}F$) + (5 year operating cost of heater for an input with mixing efficiency of 0.8)]

= £542,000 - (20,000 + 12,000(5))

= £462,000 .

As usual, a search is then carried out over D_4 for each r to determine $f_4(S_4)$ for each input state. The computation given above, for example, gives the maximum value for the input mixing efficiency of 80%.

The results of this 4-stage recursion are presented in Table IV of the tabular listing.

ii) Computation of maximum 5-stage profits

As this is the first state (in time) of the production process, there is no input state vector, to give additional states to be carried through to the other stages and complicate matters by introducing dimensionality problems. The only relevant consideration about the input is the through put quantity given as 50,000 lbs., on which basis the costs associated with the various decisions, are computed.

The decision variables at this stage are type of mixer and mixing efficiencies. Because of the low order of both decision vectors (3, 4), no computational difficulties are caused. Computation of $h(S_5, D_5)$ necessitates calculation of $3 \times 4 = 12$ values. The relevant cost information is provided in Table VII.

TABLE VII

Costs for the Mixing Operation

Mixer type	Initial cost*	Operating Costs Mixing Efficiency			
		1.0	0.8	0.6	0.5
A	10	12.0	6.0	3.0	2.0
B	15	8.0	4.0	2.5	1.5
C	25	5.0	3.0	2.0	1.0

*These costs are not explicitly stated in the table source but have been deduced from the calculations.

The transition relationship here is again very simple: the input states at stage 4 are simply a transliteration of the decisions at this stage. Thus $S_4 = D_5$. This again allows a fairly straightforward computation of $g(S_5, D_5)$.

For example, in computing $g(S_5, D_5)$ for a choice of mixer B with an efficiency of 0.8, the equation is:

[(Maximum profit for 0.8 efficiency at stage (4)] -

[(initial cost of mixer B) + operating cost of mixer B

with an efficiency of 0.8, for 5 years)]

= £462 - [(15,000 + 4,000(5)]

= £427,000.

In computing $f_5(S_5)$, since this is the final stage of the optimization procedure, a global optimum is found from among all the profit values at this stage. This global maximum is £427,000 (see Table 5 of the tabular section). It is from this global maximum value, that the backtracking procedure is done.

b) Part II - The Backtracking

The overall optimal policy (set of decisions) for maximum profit can be traced in the direction of product flows from this global optimum value ($D_n^*(S_n)$ for n = 1, ..., 5). Along with this the optimal input states can be identified at each stage S_n^* .

From the computations done, the trace provides the following results.

i) At stage 5, a value of £427,000 indicates a choice of mixer B with an efficiency of 80%, given that the through put volume is 50,000 lbs. (the only initial parameter) $(D_5^*(S_5)$.

ii) At stage 4, for an input mixing efficiency of 80%, (optimal input state, S_4^*), the maximum value for this input state of £462,000, indicates that the optimal decision is to use a heater to provide a temperature of 750°F $(D^*(S_4))$.

iii) At stage 3, the optimal state identified directly from stage 4 (simple transition relationship) gives $S_3^* = 750°F$. The maximum value associated with this state is £516,000 which is identified with a $D_3^*(S_3)$ of Reactor IB with catalyst 2.

iv) At stage 2 the more complicated transformation relationship comes into play. Recourse must be made to Table 5.4 in the text to relate (S_3^*, D_3^*) to S_2^*. From this table it is learnt that the combination of 750°F with a decision to use reactor 1B with catalyst 2 of 40%. Thus $S_2^* = 40\%$, and the maximum value for this state is £566,000 which is identified with a choice of reactor 2A. Thus $D_2^*(S_2)$ = Reactor 2A.

v) At stage 1, again, the more complicated transformation operator must be used to find the optimal state and decision.

Resort must be made to Table III above. This table indicates that with an input from reactor I of 40% and a choice of reactor IIA at stage 2, the input conversion rate at stage 1 is 80%. Thus $S_1^* = 80\%$. From Table 1 in the computer listing an input state of 80% conversion is associated with a maximum profit value of £676,000, which identifies with the decision $D_1^*(S_1)$ of "two small separators".

In this way the overall optimal policy can be identified and a prescription for optimal technology choice to achieve maximum 5-year profits might read like this:

"For an input volume of 50,000 lbs, start the process by using a mixer of type B with a mixing efficiency of 0.8. Then pass the product through a heater at 750°F and then on to the first reaction stage, using a first reactor of type B with catalyst 2. This would give a 40 percent conversion of the product, which should then be passed on to a second reactor of type A. This would give an overall 80% conversion of the product, which should then be separated in two small (rather than one large) separators. The unit selling price for this lot is anticipated to be £3.6/lbs. which would give the plant an overall 5-year profit of £427,000."[1]

It may be noted that if there were an input vector at stage 5 (initial state of the input), describing the characteristics of the input feed, a sensitivity analysis could be performed without reworking the problem. The maximum value in relation to that input could simply be

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1 Author's quote.

compared with the global maximum to assess the loss attached to starting with those input characteristics. It would also be possible to trace the best policy, given that an input of that type had to be used.

In applying this technique to the Dairy processing industry a substantial amount of ground work had first to be done to identify the states, stages, and transition relationships and to determine the costs at the individual stages $h(S_n, D_n)$. In order to do this type of exercise, one important prerequisite is an appreciation of the technological relationships (as demonstrated in the above example). This often requires going back to basic engineering principles, and this has had to be done for the Dairy processing cost optimization problem.

MAXIMUM 1- STAGE PROFIT
(£'000)

CONVERSION RATE	ONE LARGE SEPARATOR	TWO SMALL SEPARATORS	MAXIMUM
.30	388.0	382.5	388.0
.40	503.0	500.0	503.0
.45	553.0	555.0	555.0
.50	590.0	592.0	592.0
.60	650.0	652.0	652.0
.75	662.5	668.5	668.5
.80	667.5	676.0	676.0
.85	667.5	678.5	678.5
.90	685.0	693.5	693.5
.95	700.0	711.0	711.0

MAXIMUM 2-STAGE PROFIT
(£'000)

CONVERSION RATE	REACTOR 2A	REACTOR 2B	NO REACTOR	MAXIMUM
.15	278.0	375.0	0.0	375.0
.20	393.0	472.0	0.0	472.0
.25	482.0	488.5	0.0	488.5
.30	542.0	498.5	388.0	542.0
.40	566.0	513.5	503.0	566.0
.45	568.5	531.0	555.0	568.5
.50	583.5	531.0	592.0	592.0
.60	601.0	531.0	652.0	652.0

MAXIMUM 3-STAGE PROFITS
(£'000)

TEMPERATURE	REACTOR 1A	REACTOR 1B	REACTOR 1C	CATALYST	MAXIMUM
800.0	542.0	512.0	508.5	1.0	542.0
800.0	512.0	518.5	536.0	2.0	536.0
750.0	482.0	488.5	506.0	1.0	506.0
750.0	488.5	516.0	512.0	2.0	516.0
700.0	456.0	462.0	428.5	1.0	462.0
700.0	462.0	438.5	442.0	2.0	462.0
650.0	432.0	408.5	412.0	1.0	432.0
650.0	408.5	422.0	345.0	2.0	422.0

THESE ARE THE FOUR MAXIMUM VALUES REQUIRED AT STAGE 3

542.0 516.0 462.0 432.0

MAXIMUM 4-STAGE PROFITS
(£'000)

MIXING EFFICIENCY	800 F	750 F	700 F	650 F	MAXIMUM
1.00	472.0	466.0	452.0	424.5	472.0
0.80	462.0	456.0	449.5	422.0	462.0
0.60	442.0	446.0	444.5	419.5	446.0
0.50	422.0	436.0	442.0	417.0	442.0

MAXIMUM 5-STAGE PROFITS
(£'000)

EFFICIENCY	MIXER A	MIXER B	MIXER C
1.00	402.0	417.0	422.0
0.80	422.0	427.0	422.0
0.60	421.0	418.5	411.0
0.50	422.0	419.5	412.0

GLOBAL MAXIMUM

427.0

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